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Heat transfer — a review of 1997 literature

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1. Introduction

The present review is designed to encompass the English language heat transfer papers published in 1997. The papers have been categorized into a number of sub-fields. While being exhaustive, some selection is necessary. Besides reviewing the journal articles of 1997, we also briefly mention important conferences and meetings on heat transfer and related fields, major awards to heat transfer researchers and also books on heat transfer published during the year.

The first Pacific Symposium on Flow Visualization and Image Processing was held on February 2–7 in Honolulu, USA. Topics included flow-field visualization, surface visualization, digital image processing and graphical display of data sets. The 14th International Conference on fluidized bed combustion was held in Vancouver, Canada on May 11–14. A meeting on Convective Flow and Pool Boiling was held on May 18–23 in Irsee, Germany. An International Symposium on the Physics of Heat Transfer in Boiling and Condensation on May 21–24 in Moscow, Russia, included sessions on nucleation, modeling of pool and flow boiling, two-phase transpiration cooling, boiling in microgrooves and boiling and condensation in microgravity. The first International Symposium on Advances in Computational Heat Transfer, held on 26–30 May in Cesme, Turkey covered internal flow and heat transfer, single and multiphase flow, computational solutions and solution methods and experimental validation of computational solutions. The Fourth World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics (ExHFT4) was held in Brussels, Belgium on June 2–6.

The 42nd Gas Turbine and Aeroengine Congress, User's Symposium and Exhibition 'Turbo Expo-Land, Sea and Air 1997' was organized by the International Gas Turbine Institute of the ASME at Orlando, USA on June 2–5. Topics covered included film cooling, internal air systems and seals, external heat transfer, internal cooling, and experimental methods. The second International Symposium on Turbulence, Heat and Mass Transfer held in Delft, the Netherlands on June 9–12 included turbulent transport in stagnation and recirculating regions and rotating flows, numerical simulation techniques, turbulence modelling and heat transfer augmentation by turbulence control. An International Symposium on Heat Transfer Enhancement and Energy Conservation was held in Guangzhou, China on June 16–19. The Intersociety Conference on Electronic Packaging (INTERpack) was held on July 15–19 at Kohala Coast, USA. The annual National Heat Transfer Conference was held in Baltimore, USA on August 10–12. Sessions covered bubble and droplet dynamics, fire and combustion, numerical simulation, innovations in heat transfer, thermal management of electronics, heat transfer in porous media and inverse problems in heat transfer and fluid flow. A Seminar on Compact Fired Heating Units (EUROTHERM) was held on November 11–12 in Leuven, Belgium. The International Mechanical Engineering Congress and Exposition (IMECE) was held on November 16–21 in Dallas, USA. Sessions covered fire and combustion, cooling of electronics, energy transport in microstructures and experimental methods for convection heat transfer. The Tenth International Symposium on Transport Phenomena in Thermal Science and Process Engineering was held in Kyoto, Japan on November 30–December 3. The third ISHMT–ASME Heat and Mass Transfer Conference was held on December 29–31 at Kanpur, India.

Awards presented in 1997 include: the Heat Transfer Memorial Awards instituted by the ASME were presented to Dr. Sadik Kakac for significant research in transient forced convection and boiling, and Dr. Chung K. Law for outstanding contributions in the areas of droplet and spray combustion and flame structure. The Nusselt–Reynolds prize in heat transfer was given to Dr. Geoffrey F. Hewitt. The Max Jakob award (1996) went to Dr. Robert Siegel for his contributions in the field of radiative heat transfer. The Donald Q. Kern Award of the AIChE went to Dr. Allan D. Kraus for his pioneering work in applied thermal engineering.

Books on heat transfer published in 1997

Advances in Heat and Mass Transfer in Biotechnology: Proceedings, ASME IMECE
Scott Clegg (editor)
Publisher: ASME Press

Advances in Heat Transfer (Vol 30)
James P. Hartnett, Thomas F. Irvine, Young I. Cho (editors)
Publisher: Academic Press

Advances in Heat Transfer (Vol 29)
James P. Hartnett, Thomas F. Irvine, George A. Greene (editors)
Publisher: Academic Press

Annual Review of Heat Transfer (Vol 8)
Chang-Lin Tien (editor)
Publisher: Begell House

Boiling Heat Transfer and Two-Phase Flow (Series in Chemical and Mechanical Engineering)
L.S. Tong, Y.S. Tang
Publisher: Taylor and Francis

Computational Fluid Mechanics and Heat Transfer (Series in Computational and Physical Processes in Mechanics and Thermal Sciences)
John C. Tannehill, Richard H. Pletcher, Dale A. Anderson
Publisher: Taylor and Francis

Gasliquid Flow and Heat Transfer
G.F. Hewitt, P.B. Whalley
Publisher: Elsevier Science

Handbook of Heat Transfer
W.M. Rohsenow, J.P. Hartnett, Y.I. Cho (editors)
Publisher: McGraw-Hill

Handbook of Thermal Conductivity: Inorganic Compounds and Elements (Vol 4)
Carl L. Yaws
Publisher: Gulf Publishing Co.

Heat Transfer
H.S. Winterton
Publisher: Oxford University Press

Heat Transfer (Schaum's Outline Series)
J.P. Holman
Publisher: McGraw-Hill

Heat Transfer in Condensation: Proceedings of Eurotherm Seminar (47)
R. Vidil, C. Marvillet (editors)
Publisher: Elsevier

Heat Transfer in Fluidized Beds
Wirth
Publisher: Chapman

Heat Transfer in Food Cooling Applications (Series in Chemical and Mechanical Engineering)

Ibrahim Dincer
Publisher: Hemisphere

Heat Transfer Practice with Organic Media
Walter Wagner
Publisher: Begell House

Intermediate Finite Element Method: Fluid Flow and Heat Transfer Applications
Juan C. Heinrich, Darrell W. Pepper
Publisher: Taylor and Francis

International Encyclopedia of Heat and Mass Transfer
G.F. Hewitt, G.L. Shires, Y.V. Polezhaev, Iu. V. Polezhaev (editors)
Publisher: CRC Press

An Introduction to Mass and Heat Transfer: Principles of Analysis and Design and Introduction to Fluid Dynamics: Principles of Analysis and Design
Stanley Middleman
Publisher: Wiley

Introduction to Thermal Sciences: Thermodynamics Fluid Dynamics Heat Transfer (2nd ed.) and Tables of Thermodynamic and Transport Properties
R.E. Sonntag, C. Borgnakke, C.H. Wolgemuth, R.E. Henderson, F.W. Schmidti
Publisher: Wiley

Microscales of Turbulence: Heat and Mass Transfer Correlations
V.S. Arpaci
Publisher: Gordon and Breach

Microscale Energy Transport (Series in Chemical and Mechanical Engineering)
C.L. Tien, A. Majumdar, F.M. Gerner (editors)
Publisher: Taylor and Francis

Proceedings of the 32nd National Heat Transfer Conference, Baltimore (Vols 1–11)
Publisher: ASME Press

Turbulence, Heat and Mass Transfer 2: Proceedings of the Second International Symposium on Turbulence, Heat and Mass Transfer, Delft, The Netherlands
T.W. Peeters, K. Hanjalic (editors)
Publisher: Coronet Books

2. Conduction

Conduction heat transfer is reviewed in this section. The relevant subcategories appearing include the following subtopics: contact conduction/contact resistance and conductivity; composite or heterogeneous media and materials processing; laser and pulse heating, heat waves and applications; conduction in solids of arbitrary geometries; modeling and simulation, and experimental studies; thermomechanical issues; inverse problems; conduction–convection and flow effects; microelectronic heat transfer; and specialized and miscellaneous applications.

2.1. Contact conduction/contact resistance and conductivity

The papers appearing in this subcategory deal with estimation of thermal conductivity, issues encompassing contact conduction and resistance and heat transport issues due to various aspects of heat conduction. Those dealing with thermal conductivity estimation and related issues appear in Refs. [1A,3A,5A,7A,13A]. The treatment of contact conduction and contact resistance in isotropic and composite materials including theoretical, experimental and modeling studies appear in Refs. [2A,4A,6A,8A–12A,14A].

2.2. Composite or heterogeneous media and materials processing

A study dealing with thermal diffusion in periodic multilayers with application to iron/copper multilayers appears in Ref. [15A]. The effective thermal conductivity of nonlinear composite media with contact resistance is described in Ref. [17A], and the influence of periodically layered material structure on frictional temperature during braking appears in Ref. [18A]. That related to materials processing and conjugate transport in polymer melt flow through extrusion dies is described in Ref. [16A].

2.3. Laser and pulse heating, heat waves and applications

There appears to be an increased research activity in this subcategory this year. Those dealing with heat transfer mechanisms during short pulse laser heating of thin films, laser-flash measurements on ceramic materials, quantum conductance and diffusion of nanostructures, a picosecond time-resolved transient grating method for heat detection, modeling of free boundary problem to laser fusion and estimation of temperature distribution in pumped Ti sapphire lasers, impact of nucleation density on thermal resistance, and various analysis with applications to solids and alloys appear in Refs. [19A,20A,24A,27A,29A,31A,32A,34A–38A]. Issues encompassing hyperbolic nature of heat propagation and heat waves appear in various studies in Refs. [21A–23A,25A,26A,28A,30A,33A].

2.4. Heat conduction in solids of arbitrary geometries

The study of shape factors of conduction in a multiple channel slab and the effect of nonuniform temperatures is described in Ref. [39A]. The prediction of internal temperature response to conduction heating of odd-shaped solids appears in Ref. [40A] and the effect of pin fin arrangement on endwall heat transfer appears in Ref. [41A]. The enhancement of boiling heat transfer using wetting liquids with pressed-on fins at low contact forces is described in Ref. [42A].

2.5. Modeling and simulation and/or experimental studies

As usual, this subcategory almost always enjoys a wide variety of activity across a broad range of topics to include: development of mathematical models, numerical simulations employing finite element, finite difference, boundary element and the like, and analytic studies and/or experimental validations where feasible. From the numerical simulation standpoint, the developments are either contributions to numerical aspects dealing with conduction heat transfer or applications of existing techniques to investigate various aspects of heat conduction. Both steady and unsteady situations and the effects of boundary conditions are addressed from a variety of viewpoints and situations. All these appear in Refs. [43A–80A].

2.6. Thermomechanical problems

The influence of temperature in structures and materials is an important aspect in the development of advanced materials, structural integrity and design. Multiple circular inclusions in plane thermoelasticity are described in Ref. [81A]. The use of nonlinearities for improved stress analysis by thermoelastic techniques is reviewed in Ref. [82A]. A state-space approach to magneto-thermo-elasticity with two-relaxation times is studied in Ref. [83A]. Other papers dealing with transient deformation and stresses of a clay slab during drying, a plane problem of thermo elasticity with nonideal thermal contact between a die and a half space, stability of thermoelastic contact of two layers of dissimilar materials, thermostructural analysis of rotationally symmetric fibrous composite structures, thermoelastic stress analysis under nonadiabatic conditions, monitoring of transient temperature and thermal stresses in pressure components of steam boilers, and a one-dimensional transient thermal stress problem for nonhomogeneous hollow circular cylinder appear in Refs. [84A–90A].

2.7. Inverse problems and applications

The papers appearing in this subcategory range from modeling of inverse heat transfer due to conduction to engineering applications addressing inverse issues given specific data or conditions. These appear in Refs. [91A–100A].

2.8. Conduction–convection and flow effects

A study of unsteady conjugate mixed convection flow and heat transfer between co-rotating discs appears in [101A].

2.9. Microelectronic heat transfer and applications

Improving heat transfer from a flip-chip package is described in [102A]. An integrated thermal analysis of indirect air-cooled electronic chassis appears in [103A] and conjugate heat transfer with buoyancy effects from micro-chip sized repeated heaters is studied in [104A].

2.10. Specialized and miscellaneous applications

A variety of specialized and miscellaneous applications over a broad range of subject matter dealing with heat transfer due to conduction have been investigated and appear in [105A–136A].

3. Boundary layers and external flows

The papers on boundary layers and external flows for 1997 have been categorized as follows: flow influenced externally, flows with special geometric effects, compressible and high-speed flows, analysis and modeling techniques, unsteady flow effects, flows with film and interfacial effects, and flows with special fluid types and property effects.

3.1. External effects

Papers which focus on external effects document the influence of streamwise pressure gradient [12B,13B], streamwise pressure gradient with high freestream turbulence intensity [11B], and high freestream turbulence intensity with concave curvature [5B] on turbulent boundary layer heat transfer. Several studies showed the effects of embedded vortices. In one, the vortices were made with embedded generators [3B] and in another the vortices were created with an impinging cross-flow [7B]. The effect of a vortex flow on a droplet within it was documented [6B]. The droplet–vortex interaction was significant in its influence of the droplet convective heat transfer. The effect of an acoustic field on droplet heat and mass transfer [10B] was such that acoustic oscillations decreased the mean terminal velocity of the droplets and increased heat and mass transfer accordingly. Shock wave effects on the residual energy level in repeating high-energy laser beams were evaluated [14B]. The effects of gravity waves on turbulence in a stratified medium, with associated modeling implications, were discussed [9B]. The model coefficients in the heat flux equation were modified. The effect of gravity on forced convection cooling of electronic packages was assesses [8B] and the influence of an electric field on spheroidal drops was computed [4B]. The two final boundary condition effect studies dealt with flow over a back-step. In one, the effect of spatially varying thermal boundary conditions on a turbulent flow was assessed [2B] and in the other, the effect of an orthotropic porous floor segment on a laminar flow was quantified [1B].

3.2. Geometric effects

Several papers focused on geometrical effects on heat transfer. One was with heat transfer from a moving elliptical cylinder [17B] and another modeled an isothermal sphere [15B]. Two papers dealt with the three-dimensional (3D) flow in the region where a cylinder meets an endwall [30B,38B]. The effects of the large-scale, periodic unsteadiness arising from vortex shedding were discussed. Several papers focused on heat exchanger geometries; from parallel plates [21B,39B] to staggered plate optimization [22B], and plates of non-uniform lengths aligned at angles to the flow direction [36B]. Several of the papers in this category showed the influences of items which were attached to the surface, ranging from delta-wings [23B], to dimples [35B], protruding strips [18B] or ribs [24B], riblets [20B], and 3D roughness elements [34B]. In one case, the roughness was on the leading edge of a plate and the effect was on laminar-to-turbulent transition [29B]. Other geometric studies were on the effects of hills and valley on atmospheric flow heat and mass transfer [31B], and large, 3D elements simulating electronic modules [16B,28B]. Several papers dealt with impinging jet flow and heat transfer. Two were planar jets [26B,32B] and one was a circular jet with a confined exit flow [33B]. One paper numerically simulated the thermal dispersion of a line heat source [37B]. Several of the more specific geometries under study were a linear turbine cascade [25B], a compressor spool and cavity flow [27B], and air filtration through fiberglass insulation [19B].

3.3. Compressibility and high-speed flow effects

In this category, there were papers on shock–shock interaction [42B], shocks at a compression corner [51B] and film cooling introduction to a Mach 3 mainstream [41B]. Papers dealing with fluid behavior included a study of rarefied heat transfer [40B], dissociation [44B] and general nonequilibrium behavior [46B,49B]. The latter showed the effects of a contaminant, such as water vapor, on the vibrational relaxation of nitrogen and oxygen. One paper presented measurements of Gortler-type vortices in reattaching flows [45B] and another discussed the analogy between turbulent momentum and heat transport in compressible flows [50B]. Others dealt with imposed effects, such as surface roughness [43B], applied magnetic fields [52B] and an adiabatic thermal boundary condition [48B]. In a similar paper to the latter, the effect of Prandtl number on recovery factor was analyzed [53B]. Finally, the effect of a variable density was computed, as applied to internal combustion engine flow and heat transfer [47B].

3.4. Analysis and modeling

A general review of turbulence modeling was presented [56B]. More specific modeling of turbulent flows was applied to two-equation fluid mechanics modeling of a backstep flow and heat transfer situation [54B], a two-equations thermal model was applied to an impinging jet flow [60B] and a two-parameter thermal lattice model with a controllable Prandtl number [57B] was applied for general convective heat transfer calculations. Modeling of the effects of rotation was discussed [55B]. Analyses of conjugate heat transfer included flow over a heated strip [58B] and over a thin plate [61B]. Group theory analysis was applied to a horizontal moving plate [62B] and techniques were proposed for dealing with Bingham flows [59B].

3.5. Unsteady effects

Unsteadiness and stability papers included one on transition in hypersonic boundary layers [67B], another on the temperature effects on linear stability theory [65B] and a third on the growth of Rayleigh–Taylor cells [70B]. Forced flow studies included cases of a forced laminar wall jet [68B], an oscillating flat plate [69B] and a pulsatile flow in a straight tube [63B]. The latter showed an increase in heat transfer rates with pulsation amplitude, but a decrease with pulsation frequency. One paper presented experiments on a round jet to show the effects of oscillations induced by a cavity resonance [72B] while another discussed the effects on heat transfer of surface oscillations from liquid/gas interface movement [64B]. Finally, a conjugate heat transfer analysis was given for unsteady heating of a sphere in Stokes flow [66B] and an analysis was presented for the unsteady heat transfer of an expanding cylinder in cross-flow [71B].

3.6. Films and interfacial effects

Flows in this category included one on heat transfer to a rivulet [77B], another giving the temperature field variation of a sphere coated with a thin liquid film [75B], a third giving the effects of conduction through a wavy film [74B] and a fourth on the effects of intense heating to a falling film [73B]. The unsteady rocking effect on free-surface mixing was presented for a partially-filled container [76B]. A rocking frequency for optimum mixing was found.

3.7. Effects of fluid type or fluid properties

Merk–Chao series expansion [80B] and modeling with viscous dissipation [82B] were applied for computing the thermal boundary layer behavior of a non-Newtonian fluid on a stretching sheet. The effects of fluid viscoelastic behavior were discussed for a wedge flow [81B] where it was found that the heat transfer rate was greatly affected by the elastic parameter. A multicomponent coupling effect was shown to be needed to compute transport in a three-dimensional stagnation flow of a multicomponent mixture [83B]. Convective heat transfer was computed for an electrically-conductive fluid at a stretching surface [84B]. Several papers dealt with convection in flows with particles from coarse particles affecting the near-wall heat transfer [79B], to spherical aluminium particles being heated in carboxymethylcellulose solutions [78B], to air laden with spores [85B].

4. Channel flows

4.1. Straight-walled ducts including microchannel flows

A number of studies were conducted in straight-walled ducts having a variety of cross sectional shapes. A fully developed duct flow with and without heat transfer was simulated numerically using an efficient scheme which performed computations on a 'slab' of cells [12C]. An anisotropic k–ϵ turbulence model was employed to investigate turbulent heat transfer in a Couette flow [21C]. An extended theoretical model was developed for low molecular Prandtl number fluids, following the formation of Kays and Crawford [23C]. The effect of viscous dissipation on the asymptotic behavior of laminar forced convection in circular tubes was examined [24C]. The flow and temperature field of a turbulent flow in a square duct is documented experimentally using fluctuating temperature measurements [7C]. Temperature profiles were calculated for Prandtl numbers between 0.1 and 2400 in a channel where one wall was heated and the other was cooled [16C]. Three electrically heated triangular ducts were used to simulate the thermal behavior of turbulent air flows through triangular passages [10C]. Microscale heat transfer studies have increased considerably in frequency in the literature. High-speed flow in microchannels was computed at high Knudsen number [15C]. Electrokinetic effects were examined in a microchannel between two parallel plates [14C]. A linear approximation of the Poisson–Boltzmann equation was used to describe the EDL field in a microchannel [13C]. Experiments were performed to investigate the heat transfer characteristics of impingement flow of transformer oil and 3M fluorinert liquid FC-72 [26C]. The effects of compressibility and rarefaction were studied in gas flows in microchannels [9C]; similar effects were considered in smooth microtubes [5C]. The transient response of microchannel heat sinks in a silicon wafer were computed [18C]. A numerical study of the heat transfer characteristics of superfluid helium was investigated in capillary channels [20C]. Forced convection in circular ducts with slug flow and viscous dissipation was analyzed [1C]. A fast and dependable numerical method was used to solve the fully developed hydrodynamic and thermal laminar flow in singly connected cross-sections [3C]. Steady-state heat transfer in an equilateral triangular channel was studied using a 3D model [4C]. The secondary motion caused by the Lorentz force was investigated numerically in a plane channel [6C]. The combined forced and natural convection in a vertical plane channel was simulated; a series of direct numerical simulations was employed [8C]. Mixed convection was also studied in a slightly inclined rectangular duct [11C]. An experimental investigation considered the influence of acoustic excitation on the heat transfer over a flat plate [17C]. The role of partial inlet blockage on high-velocity flow in a thin rectangular duct was considered [19C]. Relaminarization associated with highly heated gas flows was investigated numerically [22C]. The heat transfer to metallic-liquid flows from a cluster of vertical parallel-plate channels was examined [2C]. Heat transfer augmentation using a porous convection-to-radiation converter was experienced in a circular duct [25C].

4.2. Irregular geometries

Ducts having unusual cross-sections or streamwise variations in cross section are considered in this section of the review. Integral transforms were used to examine the generic issue of complex channel geometries experiencing elliptic flow [27C]. Heat transfer in a spirally fluted annuli was studied for laminar, transitional and turbulent flow [30C]. Superfluid turbulence was investigated in converging and diverging rectangular channels [31C]. The passageway within a turbine blade cascade was considered using a two-equation turbulence model [32C]. The heated normal plate placed within a channel was studied using numerical methods [33C]. The influence of local flow characteristics on heat transfer in cowled finned systems was examined experimentally [34C]. A paper provided the results of a numerical study on the bayonet tube during laminar–turbulent transition for air flow [35C]. Composite correlations were presented for convective heat transfer from arrays of 3D obstacles; experiments were conducted [36C]. Free convective flow for laminar, 2D divergent channels with isothermal boundary conditions was numerically analyzed [37C]. One paper examined the irreversibility associated with fully developed heat transfer and fluid friction through singly connected ducts [38C]. The Reynolds-averaged Navier–Stokes equations were computed for flow and heat transfer in a pipe with wall suction [39C]. The effects of varying the rib geometry, the rib configuration, and the channel wall boundary conditions on heat transfer in turbine blades was investigated [40C]. One paper describes the experimental examination of the pressure drop and heat transfer of the flow in convergent and divergent ducts of rectangular cross section [41C]. The turbulent Couette flow in concentric annuli was numerically studied; the inner cylinder was slightly heated [42C]. Three-dimensional measurements of the mean velocity field in a square cross-section, curved duct flow, and the associated heat transfer were studied [43C]. A third-order finite difference method was used to study the buoyancy induced vortex flow in a forced air flow through a bottom heated plane channel [44C,45C]. The convective heat transfer in a rectangular packed duct was studied with asymmetric wall temperatures [28C]. The bifurcation structure of thermohaline-driven flows was studied using the Boussinesq model in a two-dimensional rectangular basin [29C].

4.3. Finned and profiled ducts

Extended surfaces provide a rich collection of fluid-thermal phenomena for heat transfer augmentation; a variety of experimental and numerical studies appeared in the literature. Measurements of the flow field and thermal field were reported for a flow in a periodically ribbed duct [46C]. The heat transfer near the leading edge of a gas turbine blade due to rib-roughened channels was considered [70C]. The steady compressible viscous flow of a high speed gas in a square channel with one rib-roughened wall was computed using a 3D solver [47C]. The role of plate-fin heat sinks for impinging flow was studied in air [48C]. One study considered the single-phase heat transfer characteristics in single-grooved and cross-grooved micro-fin tubes [49C]. The heat transfer inside a square ribbed enclosure was studied to mimic the reciprocating motion in marine diesel engines [50C]. The convective heat transfer was studied in a rectangular duct with drop-shaped pin fins [51C]. An isothermal analysis was conducted on a manifold microchannel heat sink [52C]. Ribbed turbulators were used to augment heat transfer in a two-pass square channel [53C]. Experiments were performed to determine the characteristics of turbulent flow inside circular finned tubes equipped with longitudinal fins interrupted in the streamwise direction [54C]. Heat transfer and fluid flow over a row of in-line cylinders placed between two parallel plates were studied numerically [55C]. A numerical investigation of laminar forced convection was conducted in a three-dimensional channel with a baffle in the entrance region [56C]. An electrochemical mass transfer technique has been employed to calculate values of the local transfer coefficients within a corrugated plate heat exchanger channel [57C]. A numerical study is presented for the heat transfer enhancement in a horizontal tube due to the insertion of an adiabatic plate [58C]. The effect of slit ribs on heat transfer and friction in a rectangular channel is investigated experimentally [59C]. Two-dimensional laminar flow and heat transfer in a channel with periodic grooves simulating electronic components were computed by solving the Navier–Stokes and energy equations using a high-order finite difference scheme [60C]. The effect of ribs with holes on heat transfer in a square channel is examined experimentally [61C]. An investigation determined the heat transfer coefficients on both a horizontally and vertically orientated simulated printed circuit board [62C]. Experiments were conducted to determine the local heat transfer performance in a rotating single-pass passage with ribs normal to the flow [63C]. Forced convective heat transfer from a micro-finned tube surface to a fluorocarbon liquid FX3250 was studied experimentally [64C]. A two-pass rib-roughened channel with a sharp 180-degree turn was studied; both friction factor and heat transfer coefficients were evaluated [65C]. Three transport-type turbulence models were compared in rib-roughened channels [66C]. An experimental investigation was carried out for fully developed turbulent flow in a rectangular duct with expanded metal mesh as artificial roughness [67C]. A numerical simulation was done on the flow and the thermal field around a plate fin array subjected to a uniform flow [68C]. The thermal-hydraulic characteristics in a spacer-ribbed annular fuel channel for high-temperature gas-cooled reactors were analyzed numerically [69C]. Local heat transfer distributions and pressure drop in a smooth circular tube with twisted tape inserts and axially interrupted ribs were investigated [71C].

4.4. Periodic flows, secondary flows and entrance effects

Secondary motion and heat transfer in curved tubes were simulated numerically [81C]. Experiments on convective heat transfer in a rectangular channel with a sharp 180° turn were conducted to clarify the local heat transfer characteristics [83C]. Experiments were carried out to examine the heat transfer in air, water and ethylene glycol in helically coiled pipes [99C]; a generic study of flow and heat transfer behavior due to centripetal acceleration was also found in the literature [91C]. A fully elliptic numerical study was carried out to investigate three-dimensional turbulent developing heat transfer in helically coiled pipes with finite pitch [87C]; entrance region effects were also considered [88C]. The temporal and spatial characteristics of thermal pulses travelling in conduits of finite wall conductivity were studied using multiple time scale expansion [86C]. The turbulence structure of the liquid phase near a wavy gas–liquid interface was investigated in a stratified rectangular duct [89C]. Pulsatile flow in a tube with constant heat flux was treated analytically to determine the heat transfer rate and the affects of Prandtl number and pulsatile frequency [90C]. Fluid mixing and mass transfer in cavities with time-periodic lid velocity were examined numerically [92C]. Numerical quadrature was used to solve the conjugate heat exchange problem [93C]. The heat transfer and fluid flow in a pipe with a sinusoidally wavy surface was studied numerically [94C] and experimentally [95C]. One study focused on developing low-dimensional models for transitional forced convective heat transfer in a periodically grooved channel [96C]; triangular versus sinusoidally varying channels were compared [97C]. The fully developed region of a horizontal circular straight tube with reentrant, square-edged, and bell-mouth inlets under isothermal and nonisothermal flow conditions was examined [98C]. A study demonstrated that at high Reynolds numbers, two-dimensional simulations significantly overpredict the heat transfer and other turbulence quantities [100C]. The dual influences of curvature and buoyancy were studied in a heated horizontal curved tube [80C]. One paper examined the two-dimensional supersonic unsteady flow in a convergent–divergent duct with heat addition [85C]. Detailed experimental results on flow resistance and heat transfer of regenerator wire meshes of a Stirling engine with oscillatory flow were found [84C]. Various forms of the Nusselt number are analyzed in pulsatile pipe flow [82C]. A numerical study is performed on the fully developed forced-convection heat transfer in a grooved channel with a heated lower plate [79C]. Unsteady heat transfer for fully developed laminar flow with a parabolic velocity profile through a parallel-plate channel, subjected to sinusoidally varying inlet temperature was considered [78C]. The concept of applying a prescribed oscillation to viscous fluids to aid or increase flow is examined [77C]. A numerical simulation of vortex shedding phenomenon in a channel with flow induced through a porous wall was undertaken [75C]. The heat transfer in high speed two-stroke engines was examined for different transfer channels [76C]. An extension of the generalized integral transform technique was used to investigate the forced convection inside a circular duct [74C]. The Graetz problem extended to include slip-flow was considered for Knudsen numbers ranging between 0 and 0.12 [73C]. Slug flow forced convection in a circular duct is studied; viscous dissipation is analyzed in the thermal entrance region [72C].

4.5. Non-Newtonian flows

The asymptotic behavior of the temperature field for the laminar and hydrodynamically developed forced convection of a power-law fluid which flows in a circular duct was studied [101C]. The problem of the interaction between viscous heating, heat transfer and flow in Couette rheometers was investigated [102C]. Constant temperature 3D mixed convection was studied for flow within a horizontal duct [103C]. A new technique using separation of variables and spectral decomposition was used to study the entrance region of a power-law fluid [104C]. The nonisothermal extrusion of viscoplastic fluids with wall slip was modeled analytically [105C]. The laminar flow heat transfer to viscous power-law fluids in a double-sine duct was computed using a Galerkin approach [106C]. The thermally fully developed and thermally developing laminar flow of a Bingham plastic in a circular pipe were studied analytically [108C] and numerically [107C]. Flow patterns and heat transfer coefficients were obtained for the fully developed flow of viscoelastic liquid flowing laminarly inside ducts of rectangular cross sections [109C]. Heat transfer enhancement in laminar flow of viscoelastic fluids through rectangular ducts was examined [110C]. The heat transfer problem that occurs during the laminar flow of a Herschel–

Bulkley fluid through the entrance region of tubes is studied [111C].

4.6. Miscellaneous duct flows

An experimental research program was undertaken to examine the influence of large-scale high-intensity turbulence on vane heat transfer [112C]. The method for numerical integration of the two-dimensional Navier–Stokes and Euler equations was extended to the solution of problems of internal aerodynamics [113C]. A constructal-theory network of conducting paths is used for cooling a heat generating volume [115C]. Mean values of the convective heat transfer coefficient for two porous structures of the rotor of a heat regenerator were measured for horizontal and vertical positions of the axis [116C]. The heat exchange through the walls of an exhaust system was examined from the standpoint of exergy analysis [117C]. An experimental study of laminar heat transfer in a one-porous-wall square duct with suction was conducted [118C]. The turbulent pipe flow in a transverse magnetic field was analyzed numerically [119C]. The heat transfer augmentation promoted by vortical structures in closed channels under the influence of a magnetic field was investigated experimentally [120C]. The circular Couette flow of temperature-dependent materials was treated using an asymptotic solution in the presence of viscous heating [123C]. The rollover phenomenon was studied in a stratified tank of liquid natural gas [114C]. The thermal behavior of three vertical inline heaters placed in narrow channels and cooled by one of two dielectric fluids was experimentally studied [121C]. The internal flow of pure vapor experiencing film condensation on the bottom wall of an included channel and the inside wall of a vertical cylinder were studied [122C]. Local and mean heat transfer coefficients in bubbly and slug flow were examined under microgravity conditions [124C]. A review of the author's collective work in the field of two-phase flow modeling was also found in the literature [125C].

5. Flow with separated regions

This section of the review will summarize papers appearing in the literature which have examined flows experiencing rapid changes in geometry leading to separation. We begin with a collection of papers considering the flow and heat transfer characteristics experienced downstream of a sudden expansion. The incompressible laminar flow of air and heat transfer in a channel with a backward-facing step was studied for steady cases and for pulsatile inlet conditions [25D]. The laminar flow of a Newtonian fluid was examined numerically in an axisymmetric pipe expansion using a finite-volume approach [19D]. A separated flow model was developed and applied to a vertical annular two-phase flow [8D]. Particle velocity and concentration statistics were measured in a vertically downward planar sudden expansion flow for large-eddy particle Stokes numbers [7D]. Numerical simulations of Navier–Stokes equations were performed for incompressible flow inside a channel with a 3D backward-facing step [5D]. One study predicted a variety of laminar flows experiencing a backward-facing step configuration; primary focus was on particle-laden flows [1D]. The fluid flow characteristics within a recirculating zone for a backward-facing step with uniform normal mass bleed were studied [27D]. A number of papers focused on the separated flow and heat transfer of bluff objects. Experiments were conducted to evaluate the unsteady behavior caused by a streamwise cavity in the nose of a blunt body [28D]. A series of experiments were performed to investigate the motion of either horizontal or vertical oscillations of a long right cylinder in a linearly stratified fluid [26D]. The turbulent flow in closely spaced staggered tube bundles was investigated numerically [23D]. Two-dimensional laminar flow and heat transfer through an array of parallel flat plates with finite thickness was studied numerically [20D]. A review of recent experimental and computational studies focused on blunt body forebody and wake flows was presented, with an emphasis on rarefied flows [16D]. Numerical studies of bluff-body wakes in a turbulent stream were compared to experimental results [13D]. The heat transfer characteristics and flow behavior of cross flow over a transversely oscillating cylinder were investigated numerically [3D] and experimentally [4D]. A direct numerical simulation of the rapid separation and reattachment of the turbulent boundary layer on a flat wall was presented [24D]. A numerical study was carried out to investigate the two-dimensional turbulent flow and heat transfer in the liquid stainless-steel-filled wedge-shaped cavity formed between rollers [22D]. An algebraic heat flux model was applied to predict turbulent heat transfer in separated and reattaching flows [21D]. The turbulent near wake of a two-dimensional body influenced by a vortex shedding-type unsteadiness due to a fixed separation on one side has been measured by a direction-sensitive, multicomponent, split-film probe [18D]. Two-equation turbulence models for velocity and temperature fields were developed to calculate wall shear flows under various flow conditions [17D]. The wall shear stress and turbulence features in swirling decaying flow were analyzed near the inner cylinder of a cylindrical annulus fitted with a tangential inlet [15D]. A global approach was used to compute the unsteady separated flow in two dimensions [14D]. An advanced finite volume code was used to obtain an enhanced partial understanding of hot gas ingress heating of a generic turbine wheelspace cavity [12D]. One paper presented numerical results of the flowfield with a single jet of cold liquid entering horizontally at the bottom of a tall tank initially filled with hotter liquid [11D]. The hypersonic flow of carbon dioxide and air around a sphere–cone Mars entry vehicle were computed [10D]. Pulsed-wire measurements of mean velocity and Reynolds stresses have been made in a spanwise-invariant, three-dimensional separated flow [9D]. Heat transfer was studied in pure critical fluids surrounded by finitely conducting boundaries in microgravity [6D]. The steady axisymmetric flow in and around a deformable drop moving under the action of gravity was studied by solving the nonlinear free-boundary problem [2D]. A numerical investigation was conducted to study the three-dimensional pulsatile flow characteristics in a symmetrical bifurcation with a branch-to-trunk ratio of 2 and a branching angle of 60° [29D].

6. Heat transfer in porous media

Research on heat and mass transfer in porous media continues to expand in several directions, with much emphasis being placed on developing a predictive model of convective transport in packed and fluidized beds and resolving different approaches in the formulation of the equations of change for stationary media. Numerical modeling dominates the literature, as has been the case for the past several years. A general review of single phase, macroscale heat transport has been presented by Batycky and Brenner [2DP].

Several basic studies are noteworthy for their fundamental nature and because they cut across the divisions chosen for this literature review. These include a Second Law analysis of heat, mass and momentum transfer in packed beds [7DP] and the development of the equations describing coupled processes and the determination of transport coefficients [1DP,9DP,10DP]. A derivation of the equations and constitutive coefficients pertaining to thermal consolidation in soils was developed based on the conservation laws applied at the microscale and an averaging method based on multiscale perturbation expansions [4DP,5DP]. Liquid flow correlations for ordered particles in packed beds were developed based on flow patters and velocity parameter for thin viscous films over complex surfaces [12DP]. Flow over a bank of tubes was modeled as a non-Darcy flow in porous medium [6DP].

Heat transfer at the boundary between a porous medium and a homogeneous fluid was developed from the flux jump conditions, and the results appear to have important implications for the flux between the solid and fluid phases of the porous medium [11DP]. Phase front propagation with moisture diffusion was theoretically treated for crystallization in one-dimensional systems [3DP]. An approximate method for predicting the interactions of conduction, convection and radiation in packed beds and are a finite amplitude analysis of compressible gas flow in porous media were also developed [8DP,13DP].

6.1. Property determinations

Determination of the effective properties of both saturated and unsaturated media is a fundamental problem ultimately related to the structure of the matrix and the assumptions that underlie the averaging of the conservation equations. One study has focused on the porosity distribution near a solid boundary [17DP]. A numerical approach to the determination of the effective thermal properties and the dispersion coefficient via the two-equation model was presented by [21DP], and conductive–radiative properties were investigated for open-cellular materials [16DP]. Thermal conductivity measurements in unsaturated packed beds were reviewed for low temperatures in the absence of convective transport [14DP].

The determination of the components of dispersion coefficients was developed analytically using a line source, and results were verified experimentally [19DP]. Some encouraging advances in measurement techniques for pulsed bed calorimetry were also reported [22DP]. The contact resistance between adjacent particles in moving beds with a stagnant interstitial gas was identified as limiting factor for heat transfer [18DP]. Experiments on the effect of shear on convective heat transfer from a heater immersed in a moving bed showed that the density adjacent to the wall is a key factor on overall heat transfer coefficient [20DP]. Heat treatment methods to control the porosity and permeability of the porous structure in naturally occurring materials were described, along with a characterization of the materials so produced [15DP].

6.2. External flow and heat transfer

A variety of studies of forced, mixed and free convective flows in saturated porous media have appeared during the past year. Relatively few, however, reported results of definitive laboratory experiments.

Research on forced convection addressed augmentation of impingement heat transfer via the use of a porous matrix fixed to the surface [29DP,30DP,36DP]. Heat transfer from surfaces imbedded in a saturated porous media for a variety of heating conditions and different Newtonian and non-Newtonian fluids was addressed as well [23DP,34DP]. Mixed convection likewise was investigated for Newtonian and non-Newtonian fluids [28DP,33DP,43DP]. The general features of these studies are to predict via numerical methods the average and local heat transfer coefficients via solutions for the velocity and temperature fields in a variety of flow regimes and geometries's.

Free convection for in steady and transient flows on a flat surface imbedded in saturated porous medium was theoretically investigated 25DP,26DP,42DP]. Both power law and Newtonian fluids were considered. The special case where the medium is thermally stratified was studied numerically with the major result being that stratification can have a major effect on the Nusselt numbers and that this effect varies with the degree of stratification [24DP]. The effects of nonuniform temperature distribution on the imbedded surface were also considered [40DP]. Free convection induced by heated spheres in an infinite medium was calculated for the complementary cases of constant wall heat flux and prescribed wall temperature [31DP,32DP,44DP].

Non-Darcy flows were analyzed for surfaces with and without mass flux (i.e., transpiration), and some attention was given to dispersion effects [39DP,41DP] and viscous dissipation [38DP]. Two phase flow and heat transfer processes for pool boiling where the active surface either a porous material or a porous coating [27DP,35DP]. A special application of a saturated porous medium as heat sink for electronic equipment cooling and the use of an approximate method to predict dryout heat fluxes were reported [37DP].

6.3. Packed and fluidized beds

Decidedly fundamental and integrative work has emerged this past year on packed and fluidized beds. Extensive literature reviews on heat and mass transfer in packed beds were presented [61DP,64DP] with a careful assessment of engineering heat transfer correlations. Development of heat transfer correlations over this extended data base was also carried out. A critical review was presented of the operational and structural non-idealities in current models of multi-tube packed bed reactors [53DP]. A generalized model for heat transfer to surfaces immersed in gas fluidized beds was developed in terms of the effective thermal properties for the particles and the interstitial gas [72DP]. Particle-to-gas heat transfer at moderate Peclet number was modeled successfully for state of minimum fluidization [75DP]. Three methods were developed to determine the effective emissivity of a gas-particle suspension in fluidized bed combustors [48DP].

Fixed beds and trickle beds were the focus of several studies aimed at understanding heat and mass transfer under periodic operating conditions and when multi-step reactions are present [49DP,58DP,94DP,95DP]. Predictions were compared with limited, specific experimental data to obtain reasonable verification of mathematical models. Heat storage in such packed beds was the focus of another study where the bed material experiences melt-freeze cyclic heating [73DP,79DP]. Packed beds of steel particles were also considered as energy storage systems for solar photovoltaic systems [57DP].

Fundamental experimental work was carried out on characterizing the flow patterns in a fluidized bed with zones of no flow [68DP], and the optimal temperature distribution for controlling cooling in a packed bed was investigated [67DP]. Gas holdup and mass transfer in solids-suspended bubble columns in the presence of structured packings were experimentally determined [77DP]. Local heat transfer coefficients around tubes in a bubbling and three-phase fluidized bed were measured, and a method to characterize bubble and particle motion from the components of the transient signals was proposed [63DP,70DP]. Bubble rise velocity and suspension viscosity in a liquid–solid fluid bed were determined via experiments [86DP]. The effect of surface vibration on heat transfer in a fluid bed was investigated using a newly developed probe [56DP]. Circulating fluid beds were characterized with respect to wall-to-bed heat transfer coefficients, voidage, immersed heat transfer surfaces, riser columns, and scaling [46DP,60DP,62DP,81DP,89DP,91DP]. Reverse flow reactors were characterized via experiments and analysis [78DP,87DP].

The data base on heat and mass transfer to immersed surfaces in fluidized beds was refined a bit for the single cylinder and tube banks 55DP,76DP,90DP]. One study considered defrosting characteristics of a horizontal array of cooled tubes immersed in a very shallow bed [47DP]. Particle motion in such beds was also the subject of a theoretical study [82DP]. The understanding of heat and mass transfer to individual particles in fluid beds was extended analytically and experimental [50DP,54DP].

A wide variety of applications and special cases were investigated for both fluidized and packed beds. These studies have deepened and extended the base of experimental data and fundamental knowledge of how fluidized and packed bed systems operate. Drag reducing polymers were added to a fixed bed to alter forced convection heat transfer rated [92DP]. The charring dynamics and temperature profiles in packed beds of green wood heat fed by an internal gas were measured [45DP], and a kinetic model for the continuous pyrolysis of polyethylene in a fluid bed reactor was developed [52DP]. Evaporation rates of liquid sprayed into superheated co-current flow of solid particles and gas was experimentally determined [59DP]. Augmentation of heat transfer rates by addition of an inert solvent to a gas–solid packed bed reactor [71DP], and steam gasification of almond shells were studied in a laboratory scale rector to determine the influence of temperature and particle size on product year and distribution within the bed [80DP]. A novel non-isothermal packed bed membrane reactor was characterized analytically [66DP], and a catalytic reformer-combustor comprising two interconnected fluidized beds was proposed gas reforming processes [74DP]. A solar-heated fluid bed reactor was demonstrated for the decomposition of methane [83DP].

Fluidized and packed bed drying processes were investigated via experiments and numerical investigations. Drying of particles in a vibrating fluidized bed [51DP] was investigated for the falling rate period. A dynamic hybrid model of thermal dewatering in a fluidized bed was developed employing neural network technique [93DP] and a three-dimensional numerical model was built upon correlation equations for the interphase heat, mass and momentum transfer [85DP]. Fluidized and packed beds were modeled such that their overall operational costs could be compared on the same basis [65DP]. A rotary kiln, such as used in slagging processes, was numerically modeled, and results were compared with field measurements [88DP].

Experimental studies were done to determine temperatures profiles within a jetting fluidized bed with a conical distributor [69DP]. Convective heat transfer in two-dimensional spouted beds was evaluated in connection with a particle coating process [84DP].

6.4. Porous layers and enclosures

Research on heat transfer in porous enclosures is dominated by studies concerning horizontal layers, vertical channels, and annular enclosures. The horizontal layer continues to attracted attention owing to its ability to yield information of a fundamental nature and engineering applicability. Environmentally related studies this past year concern hydrothermal flow in acquifers [123DP,124DP] and multilayer systems [115DP,119DP]. Forced convection with free surface transport was analyzed for channel flow [98DP]. Heat storage in porous slabs and the stability of flows were also investigated [106DP,109DP,110DP]. Conjugate heat transfer problems were solved with both environmental and engineering applications [101DP,108DP].

Investigations of annular flow and heat transfer focused on pulsating flow, increasing the resistance of insulating materials using flow structure and eccentricity, and analyzing three-dimensional situations [97DP,103DP,112DP].

Numerical investigations of free convection in porous layers and low aspect ratio enclosures examined the effects of inclination, time-dependent heating, heat sources, and wavy surfaces [96DP,99DP,111DP, 113DP,120DP]. The conjugate natural convection problem was numerically investigated for two regions separated by either a horizontal or vertical conducting wall [104DP,105DP]. Convection in enclosures of high aspect ratio was investigated to determine effects of thermal stratification, non-Darcy effects, and flow structure [100DP,121DP,122DP]. Double diffusive systems received attention with respect to non-Darcy effects, boundary conditions, and cavity shape [107DP,114DP,116DP].

Specialized investigations of heat transfer in porous media include two-phase flow in porous-channel heat sinks of the type used in the cooling of electronics [117DP], and pulsating flow in a pipe partially filled with a porous medium [102DP]. The effect of anisotropy in two-phase cavity flows was studied numerically [125DP]. Parametric limits were established on regimes of free convection in a horizontal porous corner section with a variety of thermal boundary conditions [118DP].

6.5. Coupled heat and mass transfer

The modeling of coupled heat and mass transfer in porous media via the coupled energy, species, and mass conservation equations was of greater interest during the past year than in recent years. Modeling studies were derived from fundamental problems posed for non-saturated porous media, induced stress due to rapid moisture transport, and transport in hygroscopic materials [126DP,130DP,140DP,147DP,149DP,154DP].

Situations where phase transients are present have drawn the attention of modelers as well, and a variety of process applications motivated investigation of several fundamental issues. Modeling of latent and sensible heat loads, steam generation by ohmic heating in the matrix, energy storage in packed beds, infiltration into frozen soils, and capillary porous media [132DP,156DP,158DP,160DP] were reported.

Transpired surfaces in saturated porous media are apparently an application where the full range of fundamental problems have not been considered. Research completed in the past year concerned developing closed form expressions for condensation on an imbedded plate, natural convection from a surface with opposing buoyancy effects, natural convection with thermal stratification, and mixed convection with a transpired surface [127DP–129DP,141DP].

Drying processes received both experimental and theoretical attention during the past year. Materials that were the focus of research included capillary materials, porous particulate, e.g., pebble beds and packed beds, [131DP,133DP,134DP,142DP,143DP, 150DP]. Process-related studies were typified by fundamental work on direct contact drying of a porous strip

[138DP]. Environmentally oriented studies focused on the effects of ambient conditions, heat generation, deformation of unsaturated systems, and solute concentration [137DP,148DP,151DP–153DP,157DP].

Special application-oriented studies in the modeling of simultaneous reaction and mass transfer during transformation of a non-porous to porous pellet, modeling of the carbonization process in coke, modeling the effects of finite deformations in ablating elastomers, and determining thermal stress during charring [135DP,136DP,139DP,144DP–146DP,155DP,159DP].

7. Experimental techniques and instrumentation

Many experimental results are cited in other categories of this review. The purpose of this section is to identify papers that focus on new or improved experimental measurement techniques or devices that are useful in experimental studies of heat transfer. The publications referenced in this section deal explicitly with some aspect of heat transfer measurement or other measurements that are applicable to heat transfer studies.

7.1. Heat flux and heat transfer coefficient measurements

An eddy covariance system is described to measure surface heat fluxes and fluxes of momentum, H_2O and CO_2 [3E]. A system has been developed to measure the fluid-to-particle heat transfer coefficient [7E]. Surface convective heat transfer has been measured using liquid crystals with a three-color system [6E], and on internal combustion engine components [4E] and gas turbine engine stator blades [1E]. A thermopile heat-flow meter has been used as a laser power meter [5E]. The transfer function of a thin-film heat flux sensor has been determined by analyzing the responses of two different sensors mounted adjacent to one another [2E].

7.2. Temperature measurements

A purpose-built, thin, flat thermocouple was designed for use in solid oxide fuel cells [8E]. GaAs microbridge thermocouples have been fabricated for the detection on infrared radiation [10E]. Thermocouple temperature measurement errors associated with catalytic combustion [14E], guard heat loss [17E], and low frequency noise [11E] have been quantified. Methods for estimating temperature distributions from point measurements were presented [16E,19E]. Two novel calibration techniques for high-temperature furnaces were discussed [24E]. Resistance temperature devices in the form of thin-films [21E], thick-films [23E] and cold-wires [12E] were described. A number of articles focused on noncontact optical and pyrometric temperature measurement methods [9E,13E,15E,18E,20E,22E].

7.3. Velocity and flow rate measurements

A review of hot wire anemometry in transonic and slip flows was presented [32E]. Other velocity measurement methods include an integrating flow sensor with velocity magnitude and direction capabilities [29E] and an improved four-hole directional pressure probe [28E]. Innovations in volumetric flow rate [31E] and mass flux measurements [27E,30E] were described. An application of a three-dimensional particle-image velocimetry method was described [26E]. The potential advantages of Doppler global velocimetry over particle-image velocimetry for full field flow measurement were discussed [25E].

7.4. Multiphase flow measurements

A discussion was given why inertialess optical techniques such as holographic interferometry and high-speed cinematography can enhance understanding of boiling and two-phase flow phenomena [35E]. Applications of nuclear magnetic resonance imaging and electrical impedance tomography applied to multiphase flows was analyzed [34E]. Discussions of bubble size measurement [33E] and imaging of transient flows in trickle-bed reactors [36E] were presented.

7.5. Thermophysical property measurements

Several papers reported methods to measure thermal conductivity and diffusivity in solids [37E,40E,43E], anisotropic solids [38E,41E,44E] and in liquid helium [42E]. Methods of measuring the optical properties of dielectric, crystalline, particulate solids [39E] and the emissivities of high-dielectric ceramic composites [45E] were described.

7.6. Calorimetry

Several applications of differential scanning calorimetry were presented [46E,49E,50E,53E]. Applications of traditional [51E] and micro [48E] reaction calorimeters were described. A calorimetric method was devised to measure the enthalpy of liquid droplets [52E]. A barrel calorimeter was applied to troubleshooting steam generators [47E].

7.7. Error analysis and miscellaneous methods

Three papers discussed improved uncertainty estimate methods [55E,58E,61E]. The effect of operating conditions on the dynamic response of thermal sensors was analyzed [65E]. The role of sensors in heat treatment was reviewed [56E,57E]. Several papers described various applications of thermal measurement techniques and sensors [54E,59E,60E,62E–64E].

8. Natural convection — internal flows

8.1. Fundamental studies

A limited number of fundamental studies of free convection in enclosed geometries and fluid layers were published in the past year. Studies of the Rayleigh–Benard problem and its extensions include surface tension driven instability and convection and the effect of surface waves on heat transfer [4F–6F,9F,10F]. An interesting study using a Hele–Shaw cell and concentration driven convection reports the dynamics, structure, and scaling of solutal plumes generated in the flow [3F]. A numerical study of the optimization of entropy generation in an inclined cavity was reported [2F]. The interaction of convection and thermal radiation in a square enclosure was also considered [1F].

Metallurgical applications appear as fundamental studies involving the Soret effect and physical models of alloy systems with a miscibility gap [7F,8F]. The effect of a modulated gravity field on the stability of a viscoelastic fluid layer heated from below was investigated analytically [11F].

8.2. Heat-generating fluids

A primary motivation for the continuing study of free convection in heat generating fluids is the applicability of such system to the molten core retention problem for accident scenarios connected with nuclear fission reactors. Laboratory studies on semi-scale models and direct numerical simulations have appeared this past year [12F,13F,16F]. Prandtl number effects in such systems are also under study both numerically and experimentally [14F]. On a very fundamental level, the stability and transient convection problems have received attention for a constant Prandtl number, in a two-dimensional cavity [15F,17F].

8.3. Thermocapillary flows

Thermocapillary flows under free convection received some attention, though not as much and in recent years. Experimental studies involving microgravity effects in materials production were reported from experiments conducted in a drop shaft [21F], and the effects of an axisymmetric magnetic field in a convective floating zone were determined analytically [20F]. Magnetic fields parallel to a layer heated horizontally and bounded by a free surface were investigated analytically [19F]. High Prandtl number fluids in cylindrical columns were the subject of another experimental study [18F].

8.4. Enclosure heat transfer, including annuli

Research on natural convection in enclosures this past year was dominated by problems pertaining to the horizontal layer and the rectangular cavity of moderate aspect ratio. However, several studies of tall enclosures also appeared, including the closed vertical annulus [33F,36F,45F,47F], the horizontal annulus [27F,30F,32F] and the open-ended annular cavity [26F] received attention as well.

The inclined layer and rectangular cavity were the focus of both experiments and numerical analysis [42F,46F,48F,49F]. Double diffusive layers were also considered in this vein [23F,24F,35F], as were cavities containing micropolar fluids or a fine particle suspension [31F,41F]. The control of Rayleigh–Benard convection by thermal perturbation of the lower boundary was investigated experimentally [29F]. Transient flows, induced either by time-dependent lateral or bottom heating were studied from both the stability and time-averaged perspectives [28F,39F,40F]. Related problems concern the low Mach number approximation in place of the Boussinesq approximation in transient flow and the spin up of a double diffusive system [34F,38F].

Cavities of finite wall thickness and with thermal coupling to one or more boundaries appears to be an area of study that is beginning to receive a good deal of attention [25F,37F,44F,50F]. Flow and heat transfer in a horizontal layer of two immiscible liquids was investigated experimentally and numerically [43F] and numerical studies were reported for the classical problem of a long cavity with differentially heated end walls [22F].

8.5. Vertical duct flows

Basic aspects of flow and heat transfer between vertical parallel plates, especially at large Rayleigh numbers, received attention during the year [54F–57F]. Vertical ducts of finite plate size and with one or both walls roughened by square ribs were also investigated [52F,61F]. The conjugate problem wherein the channel wall is thick was investigated [53F].

Flow in vertical tubes due either solely to free convection or in mixed convection were investigated numerically and experimentally [58F,60F,62F]. New correlations were developed for mixed convection, including variable property effects [51F,59F].

8.6. Mixed convection

Mixed convection was studied from a number of different perspectives. A major focus of the work completed during the past year is the effect of buoyancy on flow structure. Experiments were reported on the change in longitudinal vortex rolls in channel flow due to buoyancy and density inversions [64F–66F,68F,71F]. Flow in a variable cross section pipes modified by a traveling thermal wave and buoyancy effects in helicoidal pipes were investigated to determine overall Nusselt number relations [67F,69F]. Flow induced by injection of warm fluid in an initially quiescent, isothermal tall cylinder was investigated numerically [63F]. The interaction of a conductive, partial partitions in a channel flow and its effects on heat transfer were computed for a range of Reynolds and Grashof numbers. The effects of transpired boundary conditions on flow and heat transfer between counter-rotating disks was studied numerically [70F].

8.7. Complex geometries

The ongoing high interest in building thermal control and the cooling of high heat flux electronic devices has given rise to a variety of augmented free-to-mixed convection strategies that involve complex enclosure geometries. A common configuration is an otherwise well characterized, buoyancy-driven cavity flow but with either internally finned surfaces [73F–76F,78F,80F] or wall mounted heat sources [72F,84F]. Another commonly attacked problem, that of free convection in a enclosure driven by heat release form discrete volumes or areas inside continued to receive attention [79F,81F–83F,85F]. Research is beginning to emerge however on optimization of such enclosures [77F].

8.8. Miscellaneous studies

Environmental concerns, materials processing, and developing advanced heat exchanger s were the motivations for several studies involving interesting free convective flow and heat transfer. These include natural convection augmentation of heat transfer in a downhole heat exchangers [87F], the development of novel thermosyphons [93F], and the role of free convective cooling of vapor-phase pyrolysis in a laminar flow reactor [94F]. Free convection in building cooling and heating situations was studied via extensive measurements in a model room aimed at determining film coefficients of heat transfer under low ventilation conditions [90F]. Analysis was presented of double diffusive convection is a stack of enclosures with heat and mass diffusive walls [89F].

Other interesting studies include the effect of free convection on non-isothermal mixing of rheologically complex fluids, buoyancy effects during the application of a thermal gradient in vapor deposition at low pressures, and the role of convection in the heating of small particles [86F,88F,91F]. A simple model of natural convection in unsaturated air in a vertical cavity was developed and successfully compared to data in the literature [92F].

9. Natural convection — external flows

9.1. Flat plate

A number of studies were conducted on natural convection around vertical, inclined and horizontal plates. Convection around a vertical plate has been examined numerically for laminar flow of micropolar fluids [2FF] and non-Newtonian fluids [4FF]. Numerical results are presented [7FF] for flow of air and water around a semi-infinite vertical plate whose temperature varies with the axial co-ordinate. A numerical study of transient free convection of a viscous dissipative fluid on an infinite vertical plate considers different Prandtl number fluids [6FF]. A study of convection on a vertical wavy plate immersed in a non-Newtonian fluid indicates the presence of a thick boundary layer with little local variation in Nusselt number [3FF]. A differential interferometer was used to study convection and radiation from a single fin mounted on a heated horizontal base [5FF]. Flow around an inclined plate in an electrically conducting and absorbing fluid was studied with solar radiation in the presence of a transverse magnetic field [1FF].

9.2. Cylinders

A correlation using results from a number of prior experimental studies has been developed [11FF] for the Nusselt number for a horizontal circular cylinder at low Rayleigh number. Experiments describe the convective heat transfer from a heated cylinder to a fluid near its critical state [10FF]. A model predicts the heat transfer from horizontal cylinders of different cross-sectional geometry [12FF]. Analysis of the flow and heat transfer around a straight tube of elliptical cross section indicates the effects of orientation, ratio of major to minor axis and Rayleigh number [8FF]. The interaction of convection and radiation heat transfer along a thin vertical cylinder has been obtained using finite difference methods [9FF].

9.3. Mixed convection

Several papers consider interaction of body forces generated by temperature differences in a fluid and pressure forces due to an imposed forced flow. The resulting flow contains some characteristics of forced convection and some of natural convection; often it is rather difficult to analyze the interactions between the two effects. When the forced flow tends to be in the same direction as the flow generated by body forces, one has aiding or parallel flow. At other times the directions are opposite, in which case one has reverse or opposed flow. Often, of course, the vectors of the two forces are not parallel. Mixed convection from a vertically moving heated plate has been examined for both aiding and opposing flows [15FF]. Mixed convection flow generated by a line heat source in a vertical surface immersed in a porous medium has been examined [14FF] using an implicit finite difference method. Mixed convection from a horizontal plate has been studied by applying transformation group theory [13FF]. Numerical results for mixed convection from a wedge has been examined for different wall thermal boundary conditions [17FF]. Experiments on mixed convection flow in the wake behind a circular cylinder at low Reynolds numbers show significant influence of heating on vortex-shedding [16FF].

9.4. Applications and miscellaneous

A series of experiments indicates the influence of constrictions on the natural air cooling of plate fins [22FF]. Natural convection mass transfer from upward pointing pyramids has been studied using a limiting current technique over a range of Rayleigh numbers [20FF]. Thermocapillary convection in a liquid-metal zone between two co-axial solid cylinders was studied [21FF] in the presence of a uniform magnetic field with interest in applications to growth of semiconductor crystals in space. A new radioscopic flow visualization technique was used to examine natural convection during melting of binary metallic Ga–In alloys [19FF]. Superimposing rotation of a rod in Czochralski convection was studied as a control technique for reducing temperature oscillations [18FF].

10. Heat transfer from rotating surfaces

10.1. Rotating disks

A numerical study was reported for heat transfer and flow stability on a rotating disk in a chemical vapor deposition reactor [4G]. The flow between a stationary and a rotating disk was analyzed to estimate the ingress in the wheelspace in a gas turbine engine [1G]. Experimental [2G] and theoretical [3G] studies were performed on the flow and heat transfer between two counter-rotating disks.

10.2. Rotating channels

Flows have been analyzed in a heated pipe rotating about a parallel axis [10G]. Studies of concentric annuli include rotation of only the inner cylinder [6G,12G] and rotation of both cylinders [7G,13G,14G]. Studies of flow and heat transfer in channels rotating about an axis perpendicular to their main flow direction include a single pass circular channel [11G], a channel with varying aspect ratio [5G], and two-pass [8G] and three-pass [9G] square channels.

10.3. Enclosures

A variety of rotating enclosure flows have been studied including Rayleigh–Bernard convection with rotation about a vertical axis [16G], an inclined differentially heated cubic cavity [17G], a Bridgman crystal growth crucible [20G], and a floating half zone [21G]. A rotating miniature heat pipe was modeled [19G] and mixing was studied in a vertical cylinder with a rotating top [18G] and in a vessel containing a 45° pitched blade rotating impeller [15G].

10.4. Cylinders and bodies of revolution

Numerical studies have been made to investigate the transient heat transfer from a rotating and expanding cylinder in cross flow [25G], forced flow past an inclined elliptic cylinder with simulated rotation [22G] and flow parallel to the rotation axis of a body of revolution [23G]. The effect of numerical precision on rotating flow predictions is demonstrated using three examples of cylindrical geometry [24G].

11. Combined heat and mass transfer

11.1. Ablation

A number of studies consider the thermal response of ablating materials. Researchers utilized analytical, computational and experimental techniques to develop a theory of heat-mass transfer processes in thin-walled shell structures made of ablating material [2H], model the effects of thermal non-equilibrium, pyrolysis and thermochemical reaction [6H], and measure the X-ray ablation response of surfaces [1H]. In addition, studies considered the ablation of glass and copper materials during laser sampling and the mechanisms for laser ablation of rhodamine dye thin films [4H,5H]. Ablation in plasma arcs was studied via numerical simulation [3H]. The simulations focus on the ablation process and the effects caused by ablated material entering the plasma armature.

11.2. Transpiration cooling

In transpiration cooling surfaces are protected from excessive temperatures by the presence of cooler fluid. The lower temperature fluid is typically injected through a permeable surface. The study performed considers the evaporation of a volatile liquid from the surface into a laminar boundary layer [7H]. Numerical simulations were performed for a variety of thermal and flow conditions, and for air–methanol and air–water systems. Results indicate that heat transfer in the air–methanol system is more sensitive to the effects of conduction, and injection parameters [7H].

11.3. Film cooling

Film cooling is an effective method of heat transfer and very useful in protecting surfaces from the effects of thermal stress. Several studies considered the film cooling of turbine blades. The effects of coolant temperature, grid turbulence, and an unsteady wake were investigated [10H,16H]. Several numerical studies were also performed. A fully three-dimensional simulation was used to study the adiabatic effectiveness and heat transfer coefficient on a rotating film-cooled turbine blade [13H]. The performance of various two-equation turbulence models in predicting heat transfer was assessed [15H]. Also, an experimental–numerical comparison of the Nusselt number for a film-cooled rotating blade was made [14H]. Flow over flat plates was also considered. The effect of the angle of injection and also the blowing ratio on both film effectiveness and heat transfer was studied [11H,12H,17H,22H]. Film cooling may be of use in high-speed, or supersonic, flows. Under such conditions, investigation of shock wave/film cooling interaction has been performed [19H]. Other studies included the effects of flow perturbations, surfactants, non-absorbable gases, and the combined effects of buoyancy, solutal diffusion on heat and mass transfer [8H,9H,18H,20H,21H].

11.4. Jet impingement heat transfer — submerged jet

A number of studies involved heat transfer in submerged jets (air issuing into air, liquid issuing into liquid) impinging on an opposite wall. Several studies elucidating the effect variation of non-dimensional parameters such as the Reynolds number, Prandtl number, and nozzle-to-plate spacing, on heat transfer were performed [24H,28H–32H]. Several studies considered the flow field effects on heat transfer in jet impingement flows; these involved velocity and turbulence measurements, and perturbations placed on the underlying hydrodynamic field [23H,25H,26H,33H]. Studies considering the angle of impingement were also performed [35H,36H]. Numerical simulation was also used in studying heat transfer in impinging jets. The investigations focused on confined, laminar opposing jets, with and without swirl [27H,29H,30H,34H].

11.5. Jet impingement heat transfer — liquid jets

A jet in which the issuing stream has a density significantly higher than that of the ambient fluid is said to be a liquid jet. Because of their relatively high thermal conductivity liquid jets are often used for jet impingement heat transfer. A study of the local heat transfer and recovery factor of impinging circular jets was performed [37H]. The study considered several values of both the Reynolds and Prandtl numbers, and the nozzle-to-plate spacing. In addition to the aforementioned parameters, another study was performed in which the angle of impingement was varied [38H]. This allowed the prediction of the variation of the both the magnitude and the location of peak heat transfer.

11.6. Spray cooling

Spray cooling lies between submerged jets and liquid jets and consists of a stream of fluid droplets impacting on a surface and thus providing a highly effective means of local heat transfer. Numerical simulations were performed to study the assimilation of a preheated jet into a uniform stream [39H]. The numerical solution provides both temperature and velocity distributions throughout the flow-field. In addition, a new model for the prediction of spray-wall impingement was developed [40H]. The model describes the droplet diameter, velocity, and mass rate as a function of the impingement parameters and properties of the impinging droplet. The model was implemented in a hybrid Eulerian–Lagrangian two-phase flow code for the purposes of model validation and comparisons with experimental data have been made.

11.7. Drying

Heat and mass transfer are integral to drying. Recent investigations include the drying of various foods. Studies of microwave, convective, and freeze drying of fruits and vegetables were performed [45H,46H,51H,70H,91H,94H]. Measurements of both heat and mass transfer coefficients were taken for both meat and vegetables [67H,71H], and the effects of heat and moisture transfer on stress and crack formation were also investigated [41H]. Numerical studies have been extremely useful in the modeling and simulation of the drying process. Studies performed include the simulation of rotary, conveyor, and bed dryers [52H,55H,65H,81H,82H,89H,92H]. Simulation of a heat pump dryer, with a user-interface and substance property data libraries, was also performed [42H]. The radiative and convective drying of porous materials was also studied [53H,54H]. The drying of wood was also extensively studied. In order to assess the validity of the numerical simulation of oak drying in an evacuated kiln, results obtained via experiment, analytical solution, and a two dimensional model were compared [43H]. The use of superheated steam in the drying of softwood and wood chips, vacuum drying of oak, and the superheated and microwave drying of softwood were studied [44H,56H,57H,62H–64H,74H,77H]. Investigations looking into the macroscopic effects of drying on the properties of wood were also performed [50H,76H]. A variety of dryers, drying environments, and heat transfer mechanisms have been studied [47H–49H,60H,61H,66H,68H,69H,72H,73H,75H,78H,79-H,83H,86H,90H,93H]. In addition the drying of various materials, organic and inorganic, have been considered [58H,59H,80H,84H,85H,87H,88H].

11.8. Miscellaneous

A variety of studies in which heat and mass transfer occurs in combination have been performed. These include the energy separation in a jet flow, the effects of vortices on the entrainment of heat and mass, reactive flow of combustion gases, heat and mass transfer involving particles, lasers, and the use of natural convection [97H,100H,102H,104H–108H,111H,113H,115H,120H,122H,123H]. Attention was also given to heat and mass transfer in electrochemical systems [95H,99H,119H,121H,125H,126H]. Heat and water transfer was also investigated in agricultural, civil and architectural structures [103H,109H,114H,117H,118H]. In performing these studies, the underlying physical phenomena have been investigated using analytical and computational tools [96H,98H,101H,110H,112H,116H,124H]. These include two and three-dimensional computations, both direct numerical simulation and large eddy simulation.

12. Change of phase — boiling

Thermal transport phenomena associated with liquid-to-vapor phase change are addressed in the publications reviewed in this section and classified into five major categories: droplet and film evaporation (10 papers), bubble characteristics and boiling incipience (20 papers), pool boiling (37 papers), flow boiling (31), and two-phase thermohydraulics (15). In addition to these 113 papers, the interested reader will find reference to studies of evaporative and ebullient heat transfer among the papers included in: change of phase — condensation (JJ), heat transfer applications — heat pipes and heat exchangers (Q), and heat transfer applications — general (S).

12.1. Droplet and film evaporation

The 1997 archival literature provides a comprehensive review of the evaporation coefficients of water, including the effects of molecular structure, molecular collisions in the vapor phase, and heat transfer limitations [4J]. Detailed studies of specific thermofluid phenomena which influence thin film evaporation, including evaporation-induced cellular convection [10J], thermocapillary stresses on a heated, evaporating meniscus [9J], and countercurrent air flow [5J]. The fundamental equations for molecular distillation of a binary mixture were presented in [8J] and the rationale for the use of agitated thin-fim evaporators in [7J].

The thermofluid behavior of thin liquid films, formed by droplet streams and sprays, is described in several papers, including [6J] — dealing with droplet impingement on a solid surface, and [1J–3J] — dealing with heat transfer on smooth and rough surfaces, respectively.

12.2. Bubble characteristics and boiling incipience

The dynamics of vapor and gas bubbles attracted considerable attention from the two-phase flow community. Miyatake et al. [21J] develop a simple equation for predicting bubble growth, throughout the bubble growth history, for both pure liquids and binary mixtures, and Buyevich and Webbon [12J] apply a previously developed theory of bubble growth to the isolated bubble regime of pool boiling. Rashidnia [24J] describes the use of interferometry and particle tracing to observe the flow and temperature fields around several individual air bubbles attached to a solid surface.

While criteria for the detachment of vapor bubbles are considered in Ref. [19J], the departure statistics of vapor bubbles generated in electrically-pulsed capillary tubes are presented in [23J] and in flow boiling along horizontal surfaces in [14J]. A photographic study of the liquid jet which forms in the tail of a detaching R113 bubble is presented in [20J].

Complex interactions between bubbles and their surroundings are the subject of Ref. [18J] — which examines heat and mass transfer associated with vapor absorption by an injected bubble, [17J] — which explores the collapse and explosion of an immersed oxygen–hydrogen bubble subjected to a pressure pulse, and [27J] — which describes the nonlinear oscillations of multiple, interacting bubbles. Thermal transport and liquid film characteristics for bubbles sliding on inclined surfaces is discussed in [11J,29J] and bubble behavior in the near-wall region of a slurry bubble column in [16J].

Flash evaporation was the subject of several studies, including Ref. [13J] in which experimental results were used to define critical transitions in pool flash evaporation, [15J] in which predictions are offered for the maximum liquid superheat possible during a flashing leak flow, [28J] which describes the results of a transient critical flow experiment, using a convergent–divergent nozzle to simulate the break geometry, and [26J] which examines aspects of steam explosions resulting from the interaction of a water jet with a layer of a molten solid. Papers dealing with bubble nucleation during laser cleaning of surfaces [30J], along with the use of steel spheres for the passive enhancement of flash boiling [22J], and with the use of several techniques for deactivating nucleation in superheated liquids [25J] can also be found in the 1997 archival literature.

12.3. Pool boiling

The limited accuracy of ebullient heat transfer correlations and new applications of nucleate pool boiling continue to spur fundamental studies of this thermal transport mechanism. Ref. [43J] extends existing nucleate pool boiling formulations by adding the effect of transient convection associated with the wakes of the departing bubbles. An alternative, semi-analytic method is proposed in [38J], on the basis of refrigerant pool boiling data. Surface roughness and nucleation site density play a critical role in pool boiling dynamics and their effect on pool boiling heat transfer is examined in [31J,36J,52J,67J]. The choice of working fluid determines the nature of the boiling process and the magnitude of the pool boiling heat transfer coefficient. Pool boiling results for He II are reported in [44J,46J], for binary and ternary mixtures of refrigerants in [47J], and for binary mixtures of alcohols in [40J]. Pool boiling under microgravity conditions is the subject of [48J,54J].

Enhancement of pool boiling heat transfer has attracted considerable attention. A comprehensive review of the many concepts proposed and commercialized is provided in [32J]. More specific techniques are described in [35J,58J] — dealing with the effects of an electric field, in [33J] — dealing with the effects of ultrasound on the pool boiling of a refrigerant mixture, and in [42J,45J,64J] — examining various aspects of finned boiling surfaces.

Application of ebullient heat transfer to the cooling of electronic components is described in [60J,66J], to the condenser-reboiler of an air-separation plant in [55J], and to the improved understanding of laser drilling in [65J].

In boiling heat transfer, the Critical Heat Flux (CHF) represents the flux value at which vapor blankets the heater surface and the heat transfer coefficient deteriorates. While a new analytical model for CHF on vertical surfaces is proposed in [53J], extended thermodynamic similarity is the basis for CHF prediction described in [49J] and an observed dependence on bubble residence time underpins the model in [34J]. Other studies explore various parametric effects — such as heater material and thickness in [41J], heater orientation in [37J], and binary mixtures in [39J]. CHF in droplet impact cooling is the subject of [57J].

Film boiling, encountered at heat fluxes greater than CHF, has been studied for a variety of geometries, including a horizontal elliptical tube [63J] and a horizontal surface [59J]. The effect of temperature dependent properties on turbulent film boiling was explored in [56J], film boiling in binary mixtures in [50J,51J], the influence of an electric field in [62J], and the quenching process in [61J].

12.4. Flow boiling

The emergence and release of vapor bubbles from surfaces washed by a liquid flow, provide a variety of mechanisms for enhanced convective thermal transport. The onset of nucleate boiling in subcooled liquid flows is examined in [71J,94J] and the conditions required for flashing in subcooled flows in [75J].

The effect of the boiling layer on the near wall velocity profile, as well as turbulent kinetic energy, and on the turbulent diffusivity in turbulent subcooled flow boiling were explored in [90J] and [70J], respectively. Modeling studies of heat transfer in wavy annular flow and inverted annular film boiling are reported in [78J] and [77J], respectively. New heat transfer and hydrodynamic measurements for heat transfer to slug-flow under reduced gravity conditions is presented in [73J].

Flow boiling in narrow channels was examined in [81J] — focusing on refrigerants in small diameter tubes, in [82J] — addressing axially-grooved rectangular channels with discrete heat sources, and in [76J] —

exploring the flow of helium in channels narrower than a bubble departure diameter. The transition from nucleate boiling to convective boiling in finned passages, associated with compact two-phase heat exchangers, was studied by [93J]

A comprehensive experimental study of flow boiling critical heat flux in uniformly heated, vertical tubes is reported in [72J] and for vertical, rectangular parallel plates in [80J]. An energy flux approach is suggested in [69J] for correlating low velocity flow boiling CHF.

Flow boiling heat transfer of refrigerants attracted considerable attention, including studies of R134a/oil mixtures in a smooth tube [88J] and a microfin tube [98J], pure refrigerants and refrigerant mixtures in a horizontal stainless steel tube [91J], a refrigerant mixture in a smooth tube [95J], a ternary refrigerant mixture in a horizontal smooth tube [97J], and an improved correlation for microfin tubes in [79J]. Heat transfer rates and two phase flow patterns for refrigerant in tubes with helical inserts are described in [83J,84J] and in deep spirally fluted tubes in [85J]. Boiling heat transfer data in the post-CHF regime under swirl flow, for two refrigerants, as well as water, were successfully correlated in [96J].

Spray and jet impingement cooling constitute a distinct category of flow boiling behavior. Ref. [68J] describes the heat transfer rate and flow pattern due to a submerged jet impinging on a circular cylinder and [74J] deals with the cooling intensity of a water spray on a surface above the Leidenfrost temperature.

Other flow boiling studies in the 1997 archival literature, include the enhancement of heat transfer on horizontal cylinders using interference sleeves [89J], a prediction technique for the thermoacoustic wave generated by the formation and rapid collapse of bubbles [92J], and a parametric study of calcium carbonate formation during subcooled flow boiling [86J,87J].

12.5. Two-phase thermohydraulics

The design of flow boiling systems must include attention to the hydrodynamic aspects of two phase flow. Ref. [101J] describes the development and application of a thermohydraulic model for the dynamic behavior of a multiphase nuclear fuel cell. Marangoni convection in a two-layer liquid–gas system with a deformable interface is the subject of [105J] and experimental results for wave propagation in cocurrent upward flow are presented in [107J]. The development of a 3D Eulerian–Lagrangian model for dispersed flow film boiling is described in [99J,100J]. Several studies addressed two-phase flow pattern development, including [103J] — dealing with theoretical and empirical models for evaporating flow, [111J] — examining flow pattern transitions for mixtures of refrigerants, and [109J] — focusing on bubble-train flows inside capillary tubes.

Reference [108J] examines the predictive performance of pressure drop and holdup models which incorporate new relationships for the interfacial and liquid friction factors. [110J] provides experimental results and a correlations for pressure drop in highly-subcooled flow boiling in small-diameter tubes. Pressure drops during two-phase refrigerant flow in low-fin and micro-fin tubes are presented in [102J], for the flow of air/water in helicoidal pipes in [112J] and for refrigerant flow through thick and thin orifice plates in [106J]. The void fraction distribution in a kettle reboiler and in low pressure subcooled flow boiling, are examined in [104J] and [113J], respectively.

13. Change of phase — condensation

Papers on condensation during 1997 were separated into those which dealt with surface geometry effects, those on the effects of global geometry and thermal boundary conditions, papers presenting techniques for modeling and analysis, papers on free-surface condensation, and papers dealing with binary mixtures.

13.1. Surface geometry and material effects

Two papers dealt with the effects of surface waviness on condensation on a vertical surface [2JJ,3JJ], one paper discussed the effects of a wavy surface on a horizontal disk for laminar film condensation [4JJ], and a fourth discussed the effects of coating a horizontal disk with layers of silicon-modified amorphous hydrogenated carbon films of different thicknesses [1JJ].

13.2. Global geometry and thermal boundary condition effects

Three papers presented results for condensing flows within configured tubes. In the first, condensation in horizontal, integral-fin tubes of large diameter was analyzed [7JJ]; in another, the tubes were flat aluminum tubes with microchannels [5JJ], and in a third, the tubes were similar to those of the second study but were microfinned inside [8JJ]. In the fourth, a model suggested that the surface tension force was effective in enhancing condensation so long as the fin tips were not flooded by condensate. The final paper in this category was for condensation within a rotating cylinder having a scraping system [6JJ]. In this experimental study, the heat transfer coefficient was shown to increase with rotation Reynolds number.

13.3. Modeling and analysis techniques

Compact heat exchangers for condensation heat transfer were discussed, including their design methodology and their future research needs [19JJ]. Models were presented for computation of laminar free and forced film condensation on horizontal tubes [15JJ] and laminar condensation on vertical plates [18JJ]. Two papers dealt with the suitability of RELAP5 for condensation calculations — one for steam condensation on an inclined surface [13JJ] and another for condensation in a core makeup tank [14JJ]. A mathematical model was presented for predicting the performance of condensing boiler heat exchangers [12JJ]. An analysis was made of the effects of condensation on pitot tube measurements in a two-phase, vapor-droplet flow [22JJ]. Conjugate heat transfer analyses were conducted with condensation on one side of a plate and natural convection [11JJ,17JJ] with a uniform surface temperature on the other side [16JJ]. Several analyses had to do with droplet growth. In one, measurements of the multiple effects involved in the process were presented [20JJ]. Most noteworthy was that of turbulent deposition. Another paper presented post-nucleation growth computations of water micro-droplets in a supersaturated gas mixture [10JJ]. Finally, a paper presented recent developments in condensation theories and models for binary droplet growth [21JJ].

13.4. Free surface condensation

A series of similar papers was written by the same authors on condensation processes ranging from a falling sphere [25JJ], a horizontal tube [27JJ], and a horizontal elliptic tube [28JJ,29JJ]. The effect of turbulent diffusion was theoretically and experimentally investigated in the case of direct-contact condensation on a liquid layer [26JJ] where it was decided that turbulent eddy diffusion across the interface must be included. Finally, laminar free convection condensation of a saturated vapor in a near-critical thermodynamic state was numerically addressed [24JJ] and the effect of non-uniform surface tension on film condensation was described by stability analysis [23JJ].

13.5. Binary mixtures

Studies with binary mixtures included one on the nucleation and growth of binary droplets in multicomponent mixtures [34JJ] and on the effects of mixture composition on condensation of droplets [32JJ]. In the latter, strong enhancement of the growth rate of ethanol was observed if other alcohols were present. The effect of Marangoni convection was assessed, where a 40% increase in heat transfer through the condensate film was noted [33JJ]. A new method was proposed [31JJ] for measuring the diffusion coefficient in a binary mixture where it was found that the product of pressure and diffusivity appeared to be constant. Application papers involved condensation of a co-current, multi-component flow in a vertical pipe [30JJ] and nucleation and growth of a new phase of alloy in a NiTi mixture [35JJ].

14. Change of phase — freezing and melting

14.1. Melting and freezing of sphere, cylinders and slabs.

Experimental and numerical studies of melting and freezing in cylinder and slab geometries were investigated by a variety of groups. Studies in cylindrical geometry included: investigation of thermal instability during melting in an isothermally heated horizontal cylinder [1JM]; a 3D numerical study of melting inside an isothermal horizontal cylinder [2JM]; a 2D model of frost growth around a cylinder in a wet airstream [3JM] and an experimental study of melting of a horizontal ice cylinder immersed in quiescent saline flow [7JM]. Studies in the slab geometry included: an experimental study of melting of a vertical ice layer immersed in immiscible liquid [8JM]; a one-dimensional model of frost growth on a cold wall [4JM] off of a cold flat surface [5JM] and a simulation of CVD silicon carbide growth off a cold vertical reactor wall [6JM].

14.2. Stefan problems

Several studies involving Stefan problems were presented. These include: an investigation of the limit of the one-dimensional Stefan problem as the diffusivity of the solid phase approaches zero [9JM]; a one phase supercooled Stefan problem with convective boundary condition at the fixed face [10JM] and an improved formulation of the oxygen-diffusion problem in metal oxidation by transforming the problem to an analogous Stefan problem [11JM].

14.3. Ice formation in porous materials

Various studies on ice formation in food and food analogs were performed. These included: experimental freezing capabilities of a tunnel and spiral belt freezer for food [12JM]; ice growth velocity in aqueous solutions using irreversible thermodynamics versus conventional heat and mass transfer [13JM]; modeling of heat transfer during high-pressure freezing and thawing

[14JM]; and an analysis of accuracy in various simulations of food freezing [15JM].

14.4. Contact melting

Contact melting investigations included: the effects of nonlinear thermophysical properties on thermal and flow fields of the molten thin layer produced by contact melting [16JM]; a study of the interface temperature of two suddenly contacting bodies — one of them undergoing phase change [17JM]; and the study of local melting at contact spots during grinding of a nickel-based superalloy with high removal rates [18JM].

14.5. Melting and melt flows

Melting and melt flow studies are loosely grouped into those pertaining to molds or preforms; laser and plasma arc processing; differential scanning calorimetry studies; convective, thermocapillary and geological/environmental effects; and general topics.

Investigations of melting in molds or preforms included: a numerical study of mobility of molten metal through a fibrous preform during metal matrix composition processing [19JM]; a mathematical simulation of injection molding of liquid crystalline polymers [35JM]; numerical modeling of heat transfer and solidification of polymer melt flow in a channel [37JM] and interaction of plastic films with molten polymer during injection molding [43JM].

Studies of melts in laser and plasma arc processing of materials included: thermal modeling during laser drilling [27JM]; a model of substrate melting during continuous wave Nd:YAG laser cladding processing [33JM]; a study of microstructure and character of laser remelting of plasma sprayed coating on an alloy [36JM]; Marangoni effects in creating topographical features during pulsed laser texturing if Ni–P magnetic disk substrates [21JM]; a numerical simulation of temperature distribution and melt pool size in a semi-infinite body due to a moving laser heat source [40JM]; an investigation of the role of recoil-pressure-induced melt flow during laser materials processing [41JM]; the importance of the melting front velocity during CO_2 laser cutting processes [44JM]. In plasma arc processing an FEM simulation of vacuum arc remelting was presented [28JM] and plasma processing was simulated for soil melting with CFD for validation of thermal plasma arc vitrification as a treatment of contaminated soils [30JM].

Several studies assessed phase change with the use of a differential scanning calorimeter (DSC). These included: a method to experimentally measure ultra-high molar mass polyethylene fiber melt temperatures with DSC [23JM] and melting of indium by temperature modulated differential scanning calorimetry TMDSC versus traditional DSC to establish different melting freezing behavior of this standard for calibration [32JM].

Further melt studies were conducted to evaluate the effects of natural convection, thermocapillary effects, and geological/environmental effects on melts. The natural convection studies modeled transient turbulent natural convection in a melt layer with solidification [26JM]; melting resulting from coupled natural convection and exothermic heat of mixing [31JM] and an experimental study of floating half zone convection [29JM]. Thermocapillary effects in melts were studied using the 3D finite volume/Newton method in materials processing [34JM] and during instability in heat transfer in a liquid metal pool [38JM]. Lastly, geological and environmental melt flows were studied, including the basalt melt flow in the Oman ophiolite [25JM] and snowmelt from advection [42JM].

General melt and melt flow studies included: a model of phase-change and melt rheology which yields a nonlinear production of melt as a function of temperature [20JM]; a model of concentration in the melt to help minimize gas pores during solidification [22JM]; heat transfer and solidification in planar flow melt-spinning with high wheelspeeds [24JM] and an investigation of flow control of molten liquids and crust formation in tubes [39JM].

14.6. Powders, films, emulsions and particles in a melt

Studies in this area included: modeling of the mechanism of formation of spherical grains obtained by the quasi-emulsion crystallization process to improve drug delivery [45JM]; micromechanical solidification analysis to determine heat exchange between particles and base metals in particles-reinforced aluminum composites [46JM]; solidification micro-structure in spray atomized metal powders [47JM] and a discussion of various modeling representations including atomization, spraying, consolidation, solidification, and microstructural evolution in spray deposition processes [48JM].

14.7. Crucible melts

Crucible melt work included: a study showing that the temperature of the silicon melt in a crucible decreases due to evaporation of chemical species [49JM] and a simulation of electron beam melting and refining of metal in a water cooled crucible [50JM].

14.8. Glass melting and formation

Studies included: experimental analysis of an aerodynamic trap-laser heating apparatus for use in glass processing [51JM] and presentation of a 3D combustion code for use in glass melting furnaces which spatially resolves the heat transfer to the glass/batch melt surface [52JM].

14.9. Welding

Welding work included: a study of thermal stress development in a nickel-based superalloy welding with an FEM model [53JM]; an analytical analysis of 3D temperature field around the welding cavity in high or low power density beam welding [55JM] and an analysis of pulsed Nd:YAG laser welding of cardiac pacemaker batteries [54JM].

14.10. Enclosures

Phase change studies in rectangular and v-shaped enclosure studies were presented. The rectangular enclosure studies included: a numerical investigation of the effect of cyclic wall temperature on the melting and solidification of steel [56JM]; the experimental study of freezing of paraffin solutions [58JM] and a numerical analysis of S/L phase change around a single and two horizontal vertically spaced cylinders in a rectangular cavity [59JM]. In addition, a numerical simulation of the solidification process of a binary mixture in a v-shaped enclosure was presented [57JM].

14.11. Nuclear reactors

Studies relevant to nuclear reactor phase change processes included: a solution of a rigorous 3D Stefan problem to incorporate quenching or collision cascades that involve nanoscale phase transitions between the solid and liquid states of the target [60JM] and simulation of oxidic molten core–concrete interaction during a severe nuclear accident using the WECHSL code [61JM].

14.12. Energy storage

Energy storage studies included: an investigation of cold energy heat release characteristics of direct-contact heat exchange between solidified oil droplets and hot air [62JM]; heat release between oil droplets and cold water solution [63JM] and a numerical simulation of natural convection-dominated melting and solidification of a phase change material (PCM) from a finned vertical wall [64JM].

14.13. Solidification during casting

Studies analyzed solidification of an alloy by cooling the vertical sides of a rectangular mold [65JM] and during gravity die casting with experimental and FEM techniques [66JM].

14.14. Mushy zone — dendritic growth

Work in this area included: a prediction of dendrite arm spacing in unsteady and steady-state heat flow of unidirectionally solidified binary alloys [67JM] and the use of microgravity to interpret dendritic growth kinetics at small supercooling [68JM].

14.15. Metal solidification

Metal solidification work included: work on alloys; investigation of electrical, magnetic and other external effects which influence solidification; solute segregation during solidification and other general topics.

Several studies were presented on alloy solidification. This work investigated: the local nonequilibrium effect on undercooling in rapid solidification of alloys [74JM]; experimental density visualization in pure gallium–indium alloys [75JM]; modeling of copper-base alloys during rapid solidification processing [82JM] and a similarity solution for the solidification of a multicomponent alloy [92JM].

Investigation of electrical, magnetic, rotational, gravitational and other effects were investigated for their influence on metal solidification. These studies included: a numerical study of the motion of a crystal/melt interface submitted to current pulses in binary alloy solidification [72JM]; rotational effects on the convection of binary alloys unidirectionally solidified from below [81JM]; analysis of aluminum solidified with and without influence of a magnetic or electric field [86JM]; a numerical model of rapid solidification during melt spinning [87JM]; direct measurements of cooling rates in single roller melt-spinning rapid solidification [91JM]; numerical study of detached solidification for conditions in space [84JM] and during steady-state detached vertical Bridgman–Stockbarger growth [85JM].

Segregation/microstructure effects during metal solidification were studied by numerous groups. These studies included investigations of: an efficient method for coupling microscopic and macroscopic calculations in solidification [76JM]; microstructural evolution in laser surface alloying of titanium with iridium [83JM]; segregation processes at microscopic and macroscopic length scales using a new dual scale model in a binary alloy [89JM]; presentation of the governing equations for the temperature-solute coupling during solidification in a multicomponent alloy [90JM]; solute redistribution limit in coarsening dendrite arms in a binary alloy [95JM] and solute distribution during rapid solidification into an undercooled melt [93JM]. In addition, several studies were performed by the same group for both binary and ternary solute redistribution. These included: an experimental validation of continuum mixture model for binary alloy solidification [77JM]; a numerical simulation of solidification of ternary metal alloys and the ensuing macro and microsegregation patterns of solutes was developed by [79JM] and used to predict the behavior of Pb–Sb–Sn alloys [78JM].

Other solidification topics included: solidification of aluminum spray-formed billets [73JM]; an efficient multilevel GFEM approach to 3D phase-change problems including metal solidification [80JM]; modeling of solidification of molten metal droplets during atomization [88JM] and an investigation of the assumption of planar solidification during melt-substrate quenching [94JM]. Lastly, computer modeling was performed using a volume change kinetic model with coupled nucleation and growth to test the influence of C and Si on SG iron solidification for hyper and hypoeutectic compositions [69JM]. The same model was then used to estimate the influence of process parameters on the volume change phenomenon [70JM] and was further compared to experimental results for certain cases [71JM].

14.16. Crystal growth from melt

Crystal growth work included further refinement and evaluation of Czochralski (CZ) and Bridgman techniques, electrical, magnetic and gravitational effects as well as a broad spectrum of general crystal growth studies.

Work on Czochralski (CZ) crystal growth included: a numerical study of CZ growth from a turbulent melt [97JM]; thermal simulation of the CZ silicon growth process by three different models with comparison to experimental results [101JM]; numerical investigation of control of the CZ crystallization process by manipulating pulling velocity and the power inputs to the melt [106JM]; the effect of internal radiative heat transfer on the convection in CZ oxide melt [109JM]; nonlinear CZ growing process of crystals with variable thermal properties [112JM]; the use of a reduced model for online simulations of the CZ growth of single crystals [121JM]; the study of physical aspects of the growth of lead molybdate single crystals [124JM,125JM] and ensuing mechanical properties [125JM]. Additional studies included: numerical and experimental study of the thermal stresses leading to cracks in CZ grown $LiNbO_3$ single crystals [127JM]; dynamic global numerical simulation of the general CZ process [128JM] used to simulate germanium crystal growth [129JM]; heat and mass transfer analysis on interface shape during CZ crystal growth from molten silicon [131JM]; numerical simulation of transport processes during CZ growth of semiconductor compounds [133JM] and computer modeling of macro-segregation dynamics of interface and stress in high pressure liquid encapsulated CZ grown crystals [137JM].

Crystal growth by Bridgman and gradient techniques included studies of: flow fields and interface shapes during horizontal Bridgman growth of fluorides [100JM]; horizontal Bridgman growth of cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTc) [103JM]; transient axisymmetric numerical calculations of the heat and species transport for vertical Bridgman growth of GaAs [107JM]; FEM simulations of the thermal environments which promote convex interface shapes during vertical Bridgman growth of CdZnTe [110JM]; interface shape of semitransparent crystals obtained by FEM predicted Bridgman growth [120JM]; simulation and measurement of vertical Bridgman growth of β-NiAl crystal [122JM]; numerical simulation of GaAs crystal growth by the vertical gradient technique [132JM]; magnetically damped convection and segregation during Bridgman growth of PbSnTe [135JM] and a fractal theory study of solid–liquid morphology during directional solidification of alloys [126JM].

Electrical, magnetic and gravitational field effects on crystal growth studies included: electric field effects on heat and mass transfer during dielectric crystallization [134JM]; kinetics and bulk crystal growth by liquid phase electroepitaxy [138JM]; modulation of dopant segregation in floating-zone silicon growth in a magnetic field using rotation [111JM] and vibrational control of crystal growth from the liquid phase [113JM]. Lastly, studies were performed to assess magnetic damping of buoyant convection during semiconductor crystal growth in microgravity after an acceleration spike [115JM], under steady transverse residual acceleration [114JM] and with g-jitters [116JM].

General crystal growth studies included: a numerical simulation of rotating magnetic field on hydrodynamics and heat transfer in single semiconductor crystal growth processes [96JM]; assessment of crystal growth properties from surfaces [98JM]; calculation of the temperature distribution in a multiwafer (GaAs) MOVPE reactor [99JM]; convective mass transfer in liquid phase epitaxial growth of semiconductors (GaInAs) [102JM]; modeling in a two-component layer crystallization process [104JM]; correction of previous work modeling the diffusion equations to track point defects in the melt from which Si crystals are grown [105JM]; melt crystallization with direct contact cooling [108JM].

Additional studies included: numerical investigation of thermal creep in microgravity environments including buoyancy and Soret diffusion during crystal growth

[117JM]; InP crystal growth by traveling heater versus no heater movement [118JM]; a time dependent simulation of laser heated miniature pedestal growth of single crystal fibers [136JM] and investigation of the melt/solid interface shape in zone melting recrystallization processing in silicon and SiO_2 [130JM]. Lastly, two commercial software packages for the modeling of bulk crystal growth process were discussed by [123JM] and a review of the stability of skeletal and dendritic growth of crystals was presented [119JM].

14.17. Casting

Various studies of phase change in a variety of casting formats were performed along with several investigations of solute segregation during casting processing.

Studies on roll, continuous, slab, strip, squeeze and other forms of casting included: a study of the various process parameters effecting thin strip casting of steel with a twin-roll caster [139JM]; a numerical study of twin-roll casting with coupled heat and fluid flow [140JM]; coupled solidification analysis of semi-solid materials and cooling rollers in a direct rolling process [144JM]; a numerical investigation of a vertical twin-roll continuous thin-strip casting [150JM] and continuous slab casting processes for stainless steel [151JM]. Further studies included: a simulation of temperature and solid shell thickness of a continuous cast slab in a steel plant [153JM]; demonstration of control of initial solidification in continuous casting using low frequency alternating magnetic fields [154JM]; a study of coupled heat and fluid flow and the solute transport during strip casting [145JM] and a numerical study of microstructural evolution in squeeze casting of an Al–4.5% Cu alloy [141JM]. Other casting studies included: FEM thermal modeling and explicit design sensitivity analysis in investment casting [142JM]; a study of thin wall technology related to heat transfer to the mold [143JM]; a numerical simulation of flow and temperature evolution during the initial phase of steady-state solidification in ingot casting and spreading casting processes [146JM]; a study of mold filling simulation of shaped castings [147JM] and a numerical method for analysis of microporosity formation in aluminum alloy castings [148JM].

Lastly, several studies on segregation in casting were performed. These included: a model of macrosegregation due to thermosolutal convection and contraction driven flow in direct chill continuous casting of an Al–Cu round ingot [149JM] and a study of the influence of micro-scale solute diffusion and dendrite coarsening on surface macrosegregation in aluminum direct chill casting [152JM].

14.18. Splat cooling

Studies in splat cooling included: modeling of metal-droplet deposition with liquid deformation and substrate remelting [155JM]; a numerical study of solidification of liquid metal droplets impacting onto a substrate [156JM] and solidification of picoliter size molten solder impacting on a composite substrate [157JM].

14.19. Miscellaneous studies

Several phase change studies that did not fit into the above categories included: studies of ice formation on aircraft parts [158JM,161JM]; ice formation on cold tube bundles either staggered or in line by FEM numerical analysis [159JM] and conjugate analysis [160JM]; oxidation (burning) of metals at gas–solid and gas–liquid interfaces [162JM] and numerical study of unsteady heat transfer from a rotating disk with solidification [163JM].

15. Radiative heat transfer

The papers below are divided into subcategories which focus on the different impacts of radiation. Papers describing the development or application of models dominate the literature on radiative heat transfer. Papers focusing on the numerical methods themselves are reviewed in the numerical methods section under subcategory radiation.

15.1. Influence of geometry

The calculation of view factors for different geometries continues to be of interest. However, compared to previous years fewer publications addressed this topic. Byun et al. [5K] use a direct discrete-ordinate method to determine view factors of rectangular enclosures. Krishnaprakas [17K] studies view factors between inclined rectangles. The radiative interchange between nondiffuse surfaces is studied in [4K] using a generalized configuration factor scheme.

A number of papers emphasizes the influence of the geometry in radiative exchange. The radiative heat transfer in elongated spheroidal cavities is considered by Fitzgerald and Striedler [9K,10K]. Cylindrical enclosures are studied by Kim and Baek [15K] using a finite volume method. The ignition of solid fuel in confined rectangular enclosures taking into account surface radiation is studied by Baek et al. [3K]. Park and Kim [22K] present a new algorithm which separates the wall emission and medium emission in the study of axisymmetric enclosures. Sivathanu and Gore [25K] model the radiative heat transfer in a cylindrical tube using a statistical method called the discrete probability function method. The problem of planar sources and point receivers is studied by DiLaura and Santoro [7K,8K]. Conditions specific to furnaces are investigated in three publications: Yin and Jaluria [27K] use a zonal method to model radiative transport in an optical fiber drawing furnace. Guo et al. [12K] study a Czochralski crystal growth furnace and Haya et al. [13K] investigate radiation in a monoellipsoidal mirror furnace. The radiative transfer from fin arrays is considered in Refs. [16K,2K].

A significant number of publications focuses on numerical methods for radiative heat transfer. The use of discrete ordinates methods (DOM) is particularly popular: Cheong and Song [6K] propose a new discrete ordinates interpolation method to model two-dimensional enclosures with participating media. Body-fitted coordinates for two- and three-dimensional problems are employed in [21K]. An even parity method of the DOM is used by Liu et al. [20K]. Selcuk and Kayakol [24K] apply the DOM and a direct transfer method to rectangular furnaces. Abraham and Magi [1K] use DOM to model radiation in diesel engines. Ray effects in the DOM are considered in [19K]. A number of papers deal with different numerical methods: Ray effects in ray tracing methods for radiative heat transfer are considered in [18K]. Monte Carlo methods are used in [14K,23K]. Fort uses a maximum entropy formalism to obtain radiation and matter distribution functions for radiative systems in steady nonequilibrium states under the gray approximation [11K]. Nonlinear Robin-type boundary conditions are implemented using an adaptive boundary element mesh in [26K].

15.2. Participating media

Papers in this category can be divided into those which focus on emission and absorption of the media and those which deal with scattering.

Radiation transfer in molecular gases such as CO_2 [42K], CO_2 and water vapor [47K] is discussed. Nelson [51K] studies radiative heating in scramjet combustors due to emission from H_2O and OH. Soufiani and Taine [58K] study high temperature radiative properties of H_2O, CO_2, and CO. Quantum molecular dynamic studies of absorption mechanisms of two metallic atom systems have been performed in [55K]. Denison and Fiveland [38K] introduce a function which closely approximates the four-region function for wide-band absorptance of radiating gases. Khan et al. [41K] use a banded radiative heat transfer analysis accounting for spectral behavior of gas and surface to model ceramic fiber liners in industrial furnaces. Several papers deal with radiative heat transfer in combustion environments: Ammouri et al. [28K] discuss the importance of spectral models in air and oxy-fuel fired furnaces. The total absorptivity for mixtures of combustion gases and soot is studied in [31K], the total emissivity of temperature-fluctuating molecular gases in [40K]. Yan and Holmstedt present a fast, narrow-band computer model for radiation calculations in nonisothermal, nonhomogeneous combustion environments [61K]. The radiation from soot in oil-fired furnaces is discussed in [62K].

Burns and Christon [32K] investigate the efficiency of spatial domain-based decomposition for large scale parallel computing in the analysis of radiative transport in nonscattering media with nonuniform absorptivity. A mathematical model for simulation of radiative transfer in CVD reactors is presented in [39K]. Zhang [63K] reexamines the transmittance formulas of laminated layers. His work shows significant errors of geometric-optics formulas for highly-absorbing media.

A number of papers emphasize the effects of scattering of radiation: Reguigui et al. [53K] use a correlation transfer equation to describe isotropic and anisotropic scattering in suspensions of scattering particles. The interaction of fire thermal radiation with water sprays is studied in [37K]. Radiative transfer in two-dimensional cylindrical scattering media with Fresnel boundaries is considered by Wu and Liou [60K]. Scattering is also important in radiation transfer in ceramic materials [48K] as well as for soils [46K]. The details of scattering also play an important role in reflection from microstructured surfaces [35K] as well as from very rough surfaces [59K].

The combined influence of emission, absorption, and scattering is taken into account in a number of papers: The radiative transport in participating media in two-dimensional rectangular enclosures is discussed in [50K,52K]. Chai and Moder [33K] present a spatial-multiblock procedure which can be used with DOM or the finite volume method. Baek and Man [30K] use a modified DOM for an axisymmetric cylindrical geometry. Degheidy [36K] uses a maximum-entropy method for the radiative transfer in turbid media with reflective boundary conditions. Scattering, absorption, and emission play an important role in such practical problems as the radiative heat transfer in boundary-layer flows [34K], rocket plumes [29K], semitransparent thermal barrier coatings [56K,57K], as well as in photocatalytic reactors [54K]. The radiative heat transfer of a torus plasma in a large helical fusion device accounting for scattering, absorption, and emission is studied by a numerical ray emission model in [49K]. Several papers by Li and Yang [43K–45K] also deal with the inverse radiation problem in which the unknown radiation source is determined from the radiation and known optical properties of a two-dimensional scattering, absorbing and emitting medium.

15.3. Radiation combined with convection, conduction and mass transfer

This year most publications focus on two combined heat transfer mechanisms. Of those papers most deal with combined radiation and convection: heat transfer in an large-scale free and impinging turbulent jet flame is studied by Johnson et al. [68K]. Radiative and convective heat transfer in two-phase turbulent fluid flow is studied by Zaichik et al. [74K]. Radiation and convection also play a role in rocket exhaust plumes [72K], and in burner-supported diffusion flames [67K]. The influence of surface conditions on flame impingement heat transfer is studied by Baukal and Gebhart [64K]. Radiation and natural convection of wire-and-tube heat exchangers of refrigeration appliances was discussed by Tagliafico and Tanda [71K]. Convection and radiation determine the heat transfer from endoreversible heat engines [66K] as well as the IR radiance statistics of natural terrain [75K].

Fewer papers focused on radiation combined with conduction: radiation and conduction heat transfer dominate in the heating of vacuum furnaces by radiant tube burners [69K]. Radiation and conduction are also important in crystal and film growth reactors. Bergunde et al. [65K] study transport phenomena in MOVPE reactors, Nami et al. [70K] model MOCVD growth of titanium dioxide films, and Yuferev and Vasil'ev [73K] study the radiative–conductive heat transfer in semi-transparent crystals being pulled from a melt.

15.4. Intensely irradiated materials

This year only a small number of studies is concerned with intensely irradiated materials. Longtin and Tien [78K] study the laser heating of transparent fluids using multi-photon absorption. Cobbett and Cha [76K] investigate the effect of intense radiation used for pumping of solid state laser media on the optical and physical properties of the lasing media themselves. Klemick et al. [77K] model the heating of biological tissue using microwave radiation. This technique is used for the treatment of cancer by hyperthemia.

15.5. Experimental methods and properties

The few papers on this topic focus mostly on experimental methods or radiation properties. Zhang et al. [85K] report measurements of the radiative heat transfer between uncoated and doped tin oxide coated glass surfaces. Sun et al. measure the optical functions of silicon at elevated temperatures in the range of 1.13–4.96 eV [84K]. The thermal characterization of surface-micromachined silicon nitride membranes is reported in [81K]. Brasunas measures and models the frequency response of infrared detectors [80K]. Baukal and Gebhart [79K] present measurements of radiation from oxygen-enhanced/natural gas flames. Pitz-Pall et al. [82K] study the flow stability in open volumetric radiation absorbers. They find that sufficiently small absorber modules with and without additional orifice plate at the rear side will always run under stable flow conditions. Schweiger and Key [83K] present a new method for estimating downwelling shortwave and longwave radiation fluxes in the Arctic from TOVS brightness temperatures.

16. Numerical methods

Development and application of numerical methods continue to be topics of significant research. New algorithms and refinements of existing procedures are developed. In this review, the papers that focus on the application of a numerical method to a specific problem are included in the category appropriate to that application. The papers dealing with the details of a numerical method are referenced in this section.

16.1. Domain discretization

For adaptive finite-element applications, Delaunay triangulation has been used to formulate an unstructured mesh generation procedure [3N]. Three-dimensional interfaces are represented by an adaptive unstructured grid [2N]. Grid orthogonality effects are examined in calculations for turbine blades [1N].

16.2. Conduction

An ADE type method has been developed for the diffusion equation in non Cartesian coordinates [8N]. Inverse heat conduction has been considered by a number of researchers. Ref. [5N] treats the transient problem by Newton's method. The method of lines is used in [6N]. A global time treatment for the inverse problem is employed in [7N]. Optimization methods have been applied to inverse phase-change problem [4N].

16.3. Convection and diffusion

Space–time spectral element methods are developed for unsteady convection–diffusion problems [9N]. A monotonic convection–diffusion scheme is proposed for adaptive meshes [10N]. Monotonic flux-discretization schemes are described in [16N,17N]. Higher order schemes have been derived and evaluated in [11N,12N]. References [13N,14N] present a new bounded central-difference scheme. A new family of very high resolution schemes is formulated in [15N].

16.4. Radiation

A new approach is described for calculating radiative flows [18N]. Reference [20N] presents a formulation for the discrete ordinates method with embedded boundaries. The method with different orders of interpolation is examined in [22N]. High resolution schemes are applied to the discrete ordinates method [21N]. Reference [19N] describes strategies for parallelization of the discrete ordinates method.

16.5. Solution of flow equations

A pressure correction scheme based on the coupled solution of the momentum equations is shown to be more efficient than a segregated algorithm [24N]. An implicit finite-volume method has been developed with nonmatching blocks of structured grid [29N]. A fully multigrid SIMPLE algorithm is examined on a standard problem [28N]. The preconditioned conjugate gradient method is used for the solution of the pressure correction equation [37N]. An equal-order finite element method is described for the solution of the flow equations [23N]. Reference [27N] presents an unstructured grid method. Unstructured meshes are used for flow solution with periodic and pressure boundary conditions [31N–33N]. Properties of the solution on a staggered triangular grid are examined [25N]. An equal-order velocity–pressure method is presented in [34N,35N]. A pressure-correction method is formulated on collocated or non-staggered grid [26N,30N,36N].

17. Transport properties

17.1. Thermal conductivity and diffusivity

Interest continues to center on the thermal conductivity and diffusivity of uncommon materials used in various applications. Conductivity measurements are accomplished, using several test methods: guarded hot plate, calorimeter, heat-flow meter, hot wire and step-heating. Results for fibrous insulating materials are reported and used to assess the test methods employed [21P,24P,30P]. Conductivities are reported for: thermoplastics under moulding conditions and for power applications, lithium sulphate, selected compounds of gadolinium and lanthanum, graphite and HTSC cuprate crystals [8P,9P,13P,23P,27P,28P]. A number of papers treat the thermal resistance of thick specimens and the thermal and electrical resistances of selected systems [2P–4P,22P].

For fluids, thermal conductivities have been measured for dilute mixtures of 3He in superfluid 4He, non-Newtonian fluids in shear flow, polymer electrolytes are predicted, using a new scheme, for liquids and mixtures at ambient or saturated pressures. Thermodynamic and heat transfer properties are reported for the replacement refrigerants R-123 and R-134a and for the secondary refrigerant aqueous potassium formate [1P,15P,17P,18P,25P,26P]. Other works measure thermal conductivity's for toluene and *n*-heptane, the thermal properties of glasses, the thermodynamics of amino acids and small peptide transfers from water to urea–water solutions, and low temperature specific heat of CEPT 2-derived compounds [11P,12P,14P,29P,31P–33P].

For gases, a simple statistical thermodynamics method is proposed to estimate the influence of non-Boltzmann distributions on thermodynamic properties [10P] and a numerical algorithm proposed to estimate thermal conductivity from boundary temperature measurements for a homogeneous material [16P].

Food processes require knowledge of the thermal properties of various food items: electric field effects on thermal conductivity of electrorheological fluids such as milk chocolate; thermal conductivity of unfrozen and frozen strawberry and spinach; and thermal diffusivity of idli batter [6P,7P,19P].

Among the thermal properties, heat capacities are considered for paramagnetic substances at very low temperatures (1.7–30 K) and measured using a commercial modulated DSC (MDSC) [5P,20P].

18. Heat transfer applications — heat exchangers and heat pipes

There is marked activity in heat transfer enhancement by surface modification and alteration of the flow process. The fouling phenomenon is addressed by attempts to characterize the mechanism and design heat exchangers to avoid or minimize the effects.

18.1. Heat exchangers

Experimental results are reported for an array of applications, some involving exchangers constructed of unconventional materials. For shell and plate configurations test results are given for evaporators used in OTEC plants, geothermal power plants and heat pump systems; the effect of exchanger inclination on performance is studied, the dynamic behavior of a shell and tube condenser examined and the performance of two-stage evaporative coolers investigated [1Q,2Q,13Q, 21Q]. Further experiments treat cross-stream thermal dispersion in staggered tube bundle with crossflow, replacement of R22 in tube-and-shell condensers, heat transfer correlation for high Prandtl number fluid in rotator type scraped surface exchanger and an ammonia evaporator using nozzle spray with square-pitch tube bundle [3Q,12Q,17Q,25Q]. Materials are the focus for several works: ceramic heat transfer components in tubular exchangers operating at temperatures above 1000°C; a cylindrical graphite block exchanger in steel shell and a new concept for liquid–liquid plate exchanger using thermo-plastic polymers [5Q,10Q,19Q].

The mathematical modeling of heat exchangers includes: The heat and mass transfer in evaporative fluid coolers, double-effect, parallel-flow absorption chillers, transient flow in multitube two-phase condensing flow systems and the influence of finite number of baffles on shell-and-tube exchanger performance. Other efforts model: heat recovery system generator performance, a novel type high temperature heat exchanger (HTHE) employing ceramic matrix composite (CHC) materials for major parts, bayonet tube exchanger in concentric arrangement, and the time constant for double-pipe, one pass shell-and-tube exchanger with varying flow rates [14Q–16Q,18Q,20Q,22Q–24Q]. Additional papers treat the shell-and tube exchanger as used in refrigeration practice, model the dynamic behavior of industrial scale units, vapor back flow in single pass air-cooled condensers and consider steam surface condensing and improving multifunctional exchangers applied in industrial processes [4Q,6Q–9Q,11Q].

18.2. Design

Papers in this section are distinguished by the number employing the thermodynamic concepts of irreversibility of entropy production to guide design and performance analysis. This approach is used to consider real heat transformer systems, an *n*-stage, irreversible combined refrigeration system, air-side heat exchanger (condenser) performance, second law analysis for a pin-fin array under crossflow, heat recovery steam generator with minimum irreversibility, and modeling of absorption chillers with internal and external irreversibilities [28Q–30Q,36Q,38Q,40Q]. Other optimization approaches utilize total heat transfer area and a linearized cost index function, pinch analysis, a simple diagnostic model for reciprocating chillers, optimum surface condenser design, and a primer which discusses air-cool heat exchangers (ACHES) and the optimization of thermal design [27Q,34Q,37Q, 41Q,43Q]. Analysis of exchanger performance address automobile air-conditioning systems using R22/R124/R152a refrigerant mixture, a metal hydride air-conditioner, an impedance-heated fluid heat exchanger, an exchanger model for mixtures and pure refrigerant cycle simulations, and a parametric treatment of an internal-melt ice-on-coil tank [26Q,33Q,35Q,39Q,42Q]. Concluding works consider heat-exchanger net works in chemical process plants and the role of heat exchangers in current avionics systems [31Q,32Q].

18.3. Direct contact exchangers

A new approach to natural draft cooling tower design uses oriented spray-assistance to increase tower capability over that for conventional design. A combined vertical film-type absorber–evaporator exchanger finds application to water pollution prevention, desalination and chemical purification. The steady-state, counter flow, wet cooling tower is investigated theoretically, and experimental work determines the controlling mechanism involved in a new combined vertical film-type absorber–evaporator exchanger and an ethylene re-liquefaction plant is simulated numerically [44Q–48Q].

18.4. Enhancement

An overview of heat transfer enhancement, with historical notes, provides perspective to the increasing practical applications of enhancement technology and introduces a number of useful generalized studies: a correlation for louver fin geometry, optimum dimensions for fin-tube exchangers, a generic algorithm for fin profile optimization, correlation equations for friction factors and convective coefficients in tubes containing bundles of internal, longitudinal fins, and optimum dimensions of rectangular fins and cylindrical pin fins [50Q,52Q,55Q,56Q,64Q,83Q].

Experimental investigations include: fin efficiency enhancement using a gravity-assisted planar heat pipe, finned tube impact gas–solid separator for circulating fluidized bed boilers, forced vibration of exchangers during heat transfer, local and overall heat transfer around a pin-finned tube in crossflow, and a comparative study of elliptical and circular sections in one-and two-row tubes and plate fin exchangers [54Q,63Q,66Q,73Q,81Q]. Other works treat electro hydrodynamically (EHD) enhanced convective boiling of R-134a in grooved channels of subcompact exchangers and the thermal performance of pin-fin fan-sink assemblies [75Q,82Q].

Specific instances of enhancement are analyzed: Fin efficiency of extended surfaces in two-phase flow, a computational model for detailed design of plate-fin-and-tube heat exchangers for pure and mixed refrigerants, the mathematics of thermal efficiencies and tip temperatures in annular fins, and tube and fin geometry alternatives for absorption-heat-pump exchanger design [49Q,53Q,58Q,77Q]. Numerical analysis is also applied to: heat transfer and fluid flow in a wavy-fin and tube exchanger, effects of inlet flow and temperature nonuniformity on thermal performance and pressure drops in crossflow plate-fin compact exchangers, fin efficiency and the heat process for fins in multistream pate-fin exchangers, and the thermoeconomic optimization of constant cross-sectional area fins [59Q,70Q–72Q,76Q]. Enhancement of shell-and-tube exchangers in the chemical processing industry and operating problems in air-cooled exchangers are noted [68Q,79Q].

Exploration of other means for enhancing heat transfer continues. Noteworthy among these efforts are: the use of spiral motion of a liquid film to provide stability and turbulence, wing-type vortex generators (WVGS), helically fluted tube with a twisted insert, wavy plate fin-and-tube exchangers, plate exchanger with mixed chevron plates, enhancing convection by applying an electric field ('ionic wind'), corrugated plate fins, and the concept of 'chaotic advection' to characterize the heating process in fluids [51Q,57Q,60Q–62Q,65Q,67Q,69Q,74Q,78Q,80Q,84Q].

18.5. Surface effects — fouling/deposits

Works in this area fall under the mechanism of fouling/deposition, reviews of the state of knowledge in cited areas, reports of fouling experiences and the appearance of attempts to model the fouling/deposition phenomenon. Thus the conditions for crystallization fouling or scale formation are cited; the adhesion of particulate materials described in terms of colloid chemistry; the fundamentals of corrosion fouling and recent research on fouling of organic fluids are reviewed. The development of biofouling and its effects on membrane processes are reviewed and the mechanism by which biofouling layers are formed set forth in detail [87Q,94Q,98Q,101Q,104Q,106Q].

The available information on particle deposition from suspensions flowing parallel to nonporous smooth and rough surfaces is summarized. This provides a good starting point from which to consider: the development of stainless steel surfaces with low surface energy by ion implantation, $CaCO_3$ fouling in AISI 316 stainless-steel and the effect of suspended particles on crystallization fouling in plate exchangers [85Q,93Q,100Q,109Q]. Chemical fouling occurs to a cylindrical probe and finned tube bundles in a diesel exhaust environment and to heat-transfer surfaces of domestic oil-fired heat boilers. The diary industry generally must deal with the fouling of process equipment. An overview acquaints the reader with the range of problems; additional papers treat fouling (and cleaning) in milk processing and fouling by whey proteins in a multi-channel-per-pass plate exchanger [90Q–92Q,95Q,105Q]. For cooling water heat exchangers air pollution is found to contribute to fouling. Industrial crystallizer heat exchanger cooling surfaces are subject to fouling and two works are specifically focused on the high solids black liquor encountered in the forest products industry. Additional efforts center on monitoring of cooling systems and heat exchangers as an approach to controlling fouling [89Q,97Q,99Q,102Q,103Q,107Q].

The modeling and numerical analysis approach to fouling is found among a group of papers: a probabilistic, maintenance strategy for equipment subject to fouling, integrated modeling of process heat transfer with combustion fouling, impact of fouling on heat exchanger efficiency in lignite utility boilers, and the numerical calculation of deposit formation effect on exchanger efficiency [86Q,88Q,96Q,108Q].

18.6. Reactors — chemical

Heat transfer considerations focus on reactors and thermochemical transformers. A number of papers deal with the polyethylene reactor, its temperature control and effects of operating conditions on heat flow using a non-dimensional, non-equilibrium model for multicomponent condensation [111Q–114Q]. A sintered metal reactor was designed, constructed and tested using the catalytic combustion of methane and a mathematical model to predict heat conductivity and permeability. A kinetic model for the partial oxidation of methane (with Pt/MgO as catalyst) was developed using hyperbolic rate equations. A 2D heterogeneous mathematical model was used to simulate a cocurrently cooled autothermal fixed-bed reactor and a reverse-flow reactor analyzed and compared to a conventional adiabatic fixed bed reactor [115Q,116Q,118Q,119Q]. Experimental results for solid–gas thermochemical transformer models show it is essential to account for the external couplings (heat or gas) involved in this type of unit. A concluding work provides an overview of the resources available for design and operation of integrated chemical reactor-heat exchangers (HX reactor) [110Q,117Q].

18.7. Thermosyphons

Noteworthy among the papers of this section are those dealing with the miniaturization of the device and its transient operation.

The experimental results are indicated for low-temperature silicon micromachined micro heat pipe arrays using water and methanol as working fluids. Also studied are flat copper–water axially grooved miniature heat pipes fabricated using the electric-discharge-machining (EDM) wire-cutting method. Additional experiments study: performance under transient acceleration, heat-pipe use to enhance forced air convection from an array of parallel plate fins and monogroove heat-pipe enhancement with electrohydrodynamic pumping [120Q–122Q,127Q,128Q].

Modeling and numerical analysis include the following: enhanced flat miniature heat-pipes with capillary grooves, room-temperature startup from frozen state, thermal performance for optimum placement of satellite equipment, vapor flow in a disk-shaped pipe with secondary flow, boundary element approach to transient analysis, optimum design — a nonlinear programming approach, and extended Silverstein correlations for heat-pipe transport limits [123Q–126Q,129Q,130Q].

18.8. Miscellaneous

A number of papers treated topics not listed above: regenerators, energy savings and storage and implications of miniaturization technology for heat exchangers.

The Ritz Rotary Regenerator is revisited, the thermal performance of cryocooler regenerators measured, and leakage distribution estimated for steam boiler rotary units [133Q,136Q,139Q].

Energy saving is approached on a number of fronts: building design, optimizing cooling systems, heat recovery from distillation processes using absorption heat pumps and transformers, potential waste heat recovery from Basque country industry, and optimization of a natural draft heat-sink system [132Q,134Q,138Q,141Q,142Q].

Other works examine: heat transfer in a shell-and-tube latent heat energy storage exchanger, guidelines for steam injection heating, the effects of the temperature interference on the heat-transfer coefficient obtained from a Wilson plot and the heat transfer and pressure loss for compact heat sinks [135Q,137Q, 140Q,143Q].

The concluding work considers the potential impact of miniaturization technologies, i.e., microelectromechanical systems (MEMS) on energy systems and the range of devices employed in such systems [131Q].

19. Heat transfer applications — general

19.1. Aeronautics, aerospace

Aerodynamic heating tests were conducted on a 70° sphere–cone Mars entry vehicle in a high enthalpy impulse facility with air and carbon dioxide test conditions [1S]. A viscous shock layer analysis determined the reentry flow field around the forebody of a Japanese re-entry vehicle [2S]. Solutions of the chemically reacting, three dimensional Navier–Stokes equations for space shuttle trajectories were compared with flight measurements of eight trajectory locations [3S]. A design procedure exhibits full scale water droplet impingement in incompressible, inviscid flow [4S]. Modern theory of meteor motion in the atmosphere is reviewed [5S].

A computational model for simulations and design analysis of nuclear thermal propulsion systems was developed [6S]. A two-dimensional finite-difference method was used to obtain information on the thermal performance of tubular space radiators [7S].

19.2. Bioengineering

Bioheat transfer has been studied in arrays of several parallel blood vessels. It was again confirmed that the Nusselt numbers were the same as for a single vessel [8S]. A theoretical analysis describes the dynamic, one-dimensional temperature distribution including heat by perfusion [9S]. Heat dissipation was evaluated for an electro-hydraulic implantable artificial heart by in vitro experiments [10S]. Hyperthermic treatment using a reentrant resonant cavity was investigated and results showed that it is indispensable to consider blood flow in predicting performance [11S]. A numerical analysis studies hyperthermia treatment of the prostate [12S]. A method using three thermal comfort meters and the effectiveness of a thermal mannequin studies the comfort of thermal environment in a vehicle compartment [13S]. A review focuses on heat and mass transfer in biological systems above and below freezing temperatures [14S]. It is investigated whether a vertical hot plate can be used as substitute of a mannequin to simulated quasi-clothing heat transfer [15S]. A new mathematical model studies heat transfer into the skin from an air bag exhaust gas [16S]. The application of heat transfer fundamentals to the development of an instrument for speech production analysis is described [17S]. A new model for muscle heat transfer was developed using Myrhages and Ericson's description and the perfusion source term was calculated [18S]. A solution to the shaft seal problem on implantable rotary blood pumps is presented [19S]. The thermodynamics of bound-to-free phase transformation of water is studied by differential microcalorimetry and FTIR spectroscopy [20S]. Thermodynamic optimization provides the basis for the existence of finely tuned frequencies of pulsating processes of animals [21S]. A phenomenological model accounts for various effects in polymerization of bone cements during hip replacements [22S]. The recording of posture has mainly considered the effect of mechanical strain on the human body. This paper studies thermal implications [23S].

19.3. Digital data processing — electronics

A novel procedure simulated the thermoelectric effects which determine the behavior of micromachined structures [24S]. The main findings of theoretical and experimental work on development of compact air-cooled heat sinks for spot cooling of power packages are presented [25S]. An analysis determines optimal placement of heat generating electronic components [26S] and of pot core magnetic components in high frequency static convertors [27S]. Computational fluid mechanics and heat transfer analysis of a power hybrid package is described [28S] and a descriptive method for displaying heat flow in power modules is presented [29S]. A thermal demonstration displays the capability of liquid encapsulated systems to cool multichip modules packages [30S].

New equipment for pressing multilayer PCBs recently developed is based on endothermic heating by passing electric current through continuous bands of copper foil [31S]. Self-consistent solutions for allowed interconnect current density are discussed [32S]. Specific test requirements for qualifying electric resistance heating cables for commercial service are provided [33S].

19.4. Energy

An analysis is developed as a design tool for gas turbine combustors [34S] and for spark ignition engines [35S]. Significant changes in the flow field of hydrogen oxygen rocket engines are caused by nonequilibrium effects [36S]. A theoretical model describes the ignition characteristics of organic dust [37S]. The atmospheric transport and dispersion of uranium hexafluoride in an accidental release was modeled [38S]. Electrohydrodynamic enhancement of two-phase heat transfer has potential benefits in the design of refrigeration systems [39S].

A similarity law is derived for single-phase natural circulation expected in liquid metal fast reactors [40S]. A two-phase flow regime map is developed analytically and experimentally for hexagonal flow channels with and without a 36-finned rod hexagonal bundle [41S]. The passive containment cooling concepts for advanced pressurized water reactors are assessed [42S] as well as safety aspects of super critical, light water cooled and moderated reactors with double tube water rods [43S].

The fusion reactor has found attention in several studies. Design options for the cooling system are discussed and it is concluded that a optimum solution includes helium cooling of low heat flux components and water cooling of high heat flux components [44S]. Modeling of fluid mechanics, heat transfer, mobilization, aerosol phenomena, atmospheric disposal and dilution were used to assess a hypothetical worst case fusion power station accident sequence [45S]. Possible failure accidents were identified for the SEAFP reactor [46S]. Local analysis techniques avoid critical heat flux conditions [47S].

Visualization indicates that transition from annular flow to churn flow occurs at a heat transport rate well below the flooding limit in closed two-phase thermosyphons [48S]. The studies also reveal the flow pattern in inclined thermosyphons at several Bond numbers [49S]. Heat transfer is studied in a rectangular natural circulation loop containing water near its density extremes [50S]. The flow in a buoyancy driven convection loop placed in a transverse magnetic field is studied by numerical simulation [51S].

19.5. Environment

Heat transfer in the environment is this time studied from a global viewpoint. Circulation models consider climate response to CO_2 at the Hadley Center [52S]. A multiyear simulation studies tropical South America [53S] and a coalification anomaly in central France [54S]. Three models study magma budgets and steady-state activity of Vulcano and Stromboli [55S]. A three-dimensional model predicts airflow and scalar dispersion in urban canyons [56S]. 6000 continental heat flow measurements as a function of depth yielded reconstruction of a global average ground temperature history over the last 20,000 years [57S]. A simple model describes the temperature field in a semi-infinite thick aquifer [58S]. Convective flow patterns near the surface of aquifers can be induced when a critical Rayleigh number is exceeded [59S]. Theoretical formulations and model experiments were used to form a model of heat and moisture transfer in unsaturated soil [60S]. Detailed hydrometeorological measurements are the basis for a river heat budget over 495 days [61S].

19.6. Manufacturing

Gas stirred turbulent mixing [62S], powder crystallization [63S], monotonic and fluctuated cooling [64S] were studied in continuous casting. Models simulated fluctuated cooling in continuously cast steel slabs [65S]. A simple one-dimensional model can be used to study phase change manipulation for droplet based free-form fabrication [66S]. Various factors determining heat flow and temperature distribution in miniature soldering are analyzed [67S]. Heat and fluid flow are modeled in a moving gas metal arc weld pool [68S]. The dimensions of a laser weld pool are predicted by a simplified model [69S]. An analysis describes heat transfer in wire drawing [70S] and specifically in the neck region of furnace drawn optical wire [71S]. The heat transfer paths in the grinding fluid, the grains, and the work piece are investigated in creep feed grinding [72S]. A similar study was applied to the orthogonal cutting process [73S].

19.7. Processing

Cold model simulation of the liquid flow revealed the flow in a blast furnace [74S]. Mathematical modeling studied chemical reaction, motion and heat transfer of gas, lump, liquid, in a blast furnace [75S,76S]. Transient response to fuel feed was predicted in a fluidized bed boiler furnace [77S]. The fluid flow and gaseous radiation heat transfer in a natural gas-fired furnace was simulated by three-dimensional computation [78S] as was the heat transfer in a blast furnace [79S]. Pressure drop and heat transfer were measured in a thermosyphon reboiler [80S] as was the convective heat transfer from a heated roll in a calender stack [81S]. The nonlinear equations for heat conduction and transfer describe the mechanical properties of a steel cylinder during quenching [82S]. Electric body forces induce jet flow and enhance heat transfer in wire-plate corona discharge [83S]. A numerical method provides guesses for heat transfer and kinetic parameters in a fixed bed reactor [84S]. A forced convection heater was developed and demonstrated for glass tempering [85S]. A test apparatus to evaluate heat transfer of a spray was designed for strip cooling [86S]. Numerical analysis describes the heat transfer and residual stress in the deep drawing of thermoplastic composites [87S]. The cyclic mould heat transfer in epoxy moulding is analyzed [88S]. Natural convection causes defects in the photo deposition of polydiacetylene thin films and has to be avoided [89S]. A simulation process is used to determine temperature/time profiles in a hot-runner injection mould [90S]. Local heat transfer coefficients for thermal food process calculation have been assembled and tested [91S]. Tests on coffee bean roasting by hot air gave best results for 250°C air temperature and 5 min exposure [92S]. New Nusselt Reynolds correlations are reported for food cooling by water or air [93S]. Heat and mass transfer analysis simulated the temperature, water mole fractions, and unreacted cement fraction profiles in a concrete pavement during the first 72 hours of curing [94S].

20. Solar energy

Reviewed papers present research on assessment and modeling of solar radiation, solar thermal technologies, and applications of solar and renewable energy technologies including water heating, space heating and cooling, solar ponds, desalination and distillation, crop drying, detoxification, thermochemical processes and power generation. Areas of solar or renewable energy research that do not emphasize heat transfer, for example, photovoltaic or wind energy, are not included. Architectural aspects of building design and control of thermal systems are also excluded.

20.1. Radiation characteristics and related effects

Published work is divided into two major categories: measurement techniques [6T,8T], and measurement and analysis of site specific data [1T–5T,7T]. A method of summarizing annual irradiation data in distribution diagrams which can be used to calculate collectable radiation is demonstrated [10T].

Adeyefa et al. [1T] examine the effects of the Pinatubo volcanic eruption on direct solar irradiance in Nigeria and Sweden. Aerosol loading in Nigeria is also measured by Maduekwe and Chendo [7T]. Clear and cloudy sky global irradiance models are evaluated for Romania [2T]. Images from the Meteosat satellite are used to derive global irradiance for Africa [3T] and Brazil [5T]. Ref. [8T] compares the accuracy of satellite data to irradiances obtained from nearby ground measuring stations. Measured spectral irradiances are compiled for Spain beginning in 1992 [4T]. Global radiation in the Uttara Kannada region of India is estimated from data at other sites [9T]. Cheng et al. [6T] discuss the accuracy of two new pyrheliometer designs.

20.2. Flat-plate and low-concentrating collectors

The use of short-term tests to predict long-term thermal performance of collectors is evaluated by Perers [19T] and Bosanac and Nielsen [12T]. Use of an ISO 9806-1 compatible model with collector parameters obtained from linear regression analysis yielded satisfactory results for a variety of flat-plate and concentrating collectors [19T]. Fundamental heat transfer analyses in flat plate collectors are conducted for specific designs. These studies include evaluation of absorber coatings for air collectors [11T] and [14T], measurement of the heat transfer coefficient in a buoyancy driven air flow in a tilted rectangular cavity [13T], First Law analysis of a solar air heater with a plastic film cover [16T], development of heat transfer correlations for wind losses from laboratory data

[17T], and derivation of a collector efficiency factor for rectangular duct collectors [20T]. An air collector that acts as a counterflow heat exchanger to preheat the air before it passes through a porous absorber is analyzed by Mohamad [18T]. A solar air heater integrated into the building is tested [15T]. This collector uses profiled steel cladding and polycarbonate sheeting.

Studies of low-concentration collectors include determination of incidence angle modifiers for tubular collectors [21T], measurement of the effect of absorber shape on optical performance of evacuated collector tubes [23T], and comparison of static and dynamic models of evacuated collectors [22T].

20.3. Concentrating collectors and systems

Papers cover topics ranging from design of high-flux concentrators, measurement and models of heat transfer processes in receivers, use and design of parabolic-trough collectors, power plant operation, and description of test facilities.

Design of concentrators for photovoltaic cells are proposed and analyzed by Ries et al. [32T]. They suggest that for a maximum concentration of 500 suns, the kaleidoscope design is a good choice. It is compact with low optical losses and homogeneous flux. A model for design of paraboloidal dish collectors is compared to experiments by Bannister and Mayer [25T]. Shortis and Johnston [33T] presents a method to assess the quality of paraboloidal concentrators from photogrammetry measurements of the three-dimensional surface.

Modeling and design of parabolic troughs is discussed in Refs. [24T,27T,30T,36T]. Almanza et al. [24T] evaluate bending of the tubular receiver when cool water is introduced. Analytical solutions of temperature profiles and thermal power delivery are presented by Fraidenraich et al. [27T]. Ref. [30T] models steam production. The use of secondary reflectors to increase the concentration onto the absorber tube are modeled with a ray trace [36T].

Solar receivers absorb concentrated sunlight and transfer the energy to a working medium. Ref. [26T] shows that the directional features of the irradiation affect absorption characteristics and illustrates the significance for two volumetric receivers. Performance of a volumetric receiver with wire mesh screens is developed and tested by Hellmuth and Matthews [28T,29T]. A description of the Directly Irradiated Annular Pressurized Receiver (DIAPR) is presented in Ref. [31T]. It is capable of supplying gas at 1300°C at 10 to 30 bar. In two papers [34T] and [35T] optimized performance of volumetric and surface absorbers are investigated and compared.

20.4. Solar water heating

Studies of water heating systems include measurement of mixed convection heat transfer in and modeling of thermosyphon heat exchangers [37T], field performance of a new system which uses photovoltaic collectors rather than thermal collection [38T,39T], simulation of night time losses in a integrated collector-storage system [41T], comparison of polypropylene and steel tubes in thermosyphon collectors [42T], effect of electric auxiliary heat on thermosyphon collectors [43T], and a discussion of the effect of various procedures used to model piping on dynamic behavior of systems [44T]. Experiments with a heat pump water heater that used flat-plate collectors with photovoltaic modules bonded to the upper surface indicate that the photovoltaic modules did not appreciably affect performance of the heat pump [40T].

20.5. Space heating and cooling

Papers on solar systems as well as heat transfer aspects of the building envelope (primarily walls, roofs and floors) are included. Papers on solar air heating concern the collector and are discussed in the section on flat-plate collectors.

Various aspects of heat and mass transfer in buildings are considered. Papers include models of the thermal storage effects [68T], and transient heat transfer and moisture transport in walls [53T,61T,63T,71T], floors and in-ground spaces [51T,62T], roofs [46T,48T,49T,69T], and single rooms [67T]. The radiative effect of glazed spaces are discussed in terms of convective patterns in atriums [52T] and cooling loads in sunspaces [73T]. Ref. [66T] considers the radiative effect of multiple buildings on heating and cooling loads of individual buildings. A new large scale environmental test chamber in Montreal for evaluation of heat, moisture and ventilation properties of building components is described [58T].

Thermal and economic performance of a solar assisted heat pump are compared to those of a conventional heat pump and a solar air heater operating in Cairo [45T]. The effect of cyclic operation of a ground-coupled heat pump is presented by Wibbels and Denbraven [75T].

The majority of papers on cooling and refrigeration address absorption cooling. The effect of noncondensable gasses on heat and mass transfer of falling lithium bromide, LiBr, films are compared to limited data [50T]. Experimental work by Kim et al. [60T] indicates that lithium bromide has higher effective absorption rate that lithium chloride. In a comparison of aqueous salt solutions, Malik and Siddiqui [65T] recommend LiBr at low evaporator temperatures and LiBr mixtures at high temperatures. Eissa [54T] recommends a 50% *n*-butane/*n*-heptane hydrocarbon mixture for solar absorption. Use of a heat recovery absorber in a solar ammonia absorption cycle improves system performance by as much as 36% [70T]. Solid absorption for solar refrigeration is evaluated in Refs. [56T,57T,72T,74T]. Experimental work by Wand et al. [74T] shows that activated carbon fiber might be substituted for activated carbon–methanol. Elsayed and Chamkha [55T] develop a model to predict the steady periodic performance of a radial flow desiccant wheel.

Numerous papers addresses reduction of cooling loads through novel roof design. Use of reflective materials and coatings are examined in Refs. [48T,49T,69T]. Addition of gravel to increases the thermal resistance of the roof is tested by Al-Turki et al. [46T]. Antonopoulos and Tzivanidis [47T] solve the three-dimensional heat transfer problem of cooling with cool water forced through pipes embedded in the ceiling slab. Kumar et al. [64T] analyze the use of a air cavity to reduce heat gain. Khedari et al. [59T] suggests that the roof can serve as a solar collector that reduces the fraction of solar energy absorbed by the roof and induces natural ventilation.

20.6. Storage

Studies of latent storage include experimental and numerical simulation of the transient heat transfer in Gypsum board impregnated with phase change material [77T], and analytical and numerical characterization of solidification in a tube [85T] and an annulus [86T].

Several papers model sensible storage seasonal storage systems in Greece [76T], Sweden [78T], and the University of Alabama [79T]. A model of heat and moisture transport in ground based storage is validated by experiment [82T]. Estimation of ground temperature is presented in Refs. [80T,83T]. Storage walls and columns in buildings are modeled by [81T] and [84T].

20.7. Stills and desalination

Common sea water desalination systems are surveyed and compared by Kalogirou [90T]. The effect of water depth and absorptivity on evaporation are studied numerically [91T]. Ref. [88T] considers the effect of water film cooling of glass covers. Ref. [87T] shows that use of a large fraction of the latent heat of condensation of the distillate to preheat and evaporate the feedstock can triple overall productivity. Ref. [92T] model thermal inertia effects for extreme operating conditions. Models of a multistage flash distillation system are used to compare performance with flat-plate and compound parabolic collectors [89T].

20.8. Ponds

The effect of various parameters on the stability of the salinity gradient in solar ponds is the subject of most papers. Ref. [94T] analyzes the influence of non-constant diffusion coefficients. Ref. [95T] measured the effects of wall angle, salt type and surface roughness on the generation of convective cells. Ref. [97T] compares gradient zone pumping and rising pond methods of controlling gradient stability. Thermal performance of a hot water pond with top and bottom insulation is compared to a salt gradient pond. The use honeycomb encapsulated with Teflon is predicted to provide double the average annual efficiency of a conventional salt gradient pond [93T]. Seawater solar ponds are evaluated for protection of fish crops along the Texas coast [98T] and [96T].

20.9. Drying

Solar drying of crops is receiving renewed interest. Empirical correlations of moisture content are presented for ambient and crop properties [99T]. Fan operating time can be reduced with microprocessor control of the exhaust fan based on moisture content of the air and crop [100T]. Ref. [102T] present a sensitivity analysis for the drying process. Ref. [101T] model a reverse flat plate collector and compare it to conventional cabinet dryers. Simulation of a packed bed of particles is used to predict performance of dying slices of food [104T]. Other applications modeled are drying of wood [105T] and rubber [103T].

20.10. Solar detoxification

Overviews of the technology and economics of solar photocatalytic detoxification of water are provided in Refs. [107T,108T]. Destruction of bacteria is demonstrated in aqueous solutions [106T] and air [109T]. A solar-powered fiber optic cable for destruction of organic pollutants is compared to a UV system [111T]. Ref. [112T] uses a Plexiglas reactor for photocatalytic detoxification of ground water contaminated with nitro aromatic compounds from an ammunition plant. A high photonic efficiency anatase titanium dioxide is investigated by Lindner et al. [110T].

20.11. Thermochemical

Concentrator and reactor design for high temperature thermochemical reactions and industrial processes are presented in the section on concentrating systems. High temperature solar reactions considered include photochemical production of fine chemicals at concentrations of 20 and 1000 suns [114T], thermal cracking of liquid petroleum [115T], reaction of coal and magnetite for gasification of coal and reduction of iron oxide [116T], use of an FT-IR systems for monitoring of photochemical processes in a high temperature laboratory furnace [113T].

20.12. Power generation

Papers on concentrators and receivers are discussed in Concentrating Collectors and Systems. Papers included here address specific installations or utility systems. Power generated by systems in Southern Nevada is predicted with various performance codes [117T]. The systems are evaluated in terms of meeting peak demand. The impact of deployment of solar generation technologies in US utility systems on greenhouse gas emissions is discussed by Martin [121T]. The effect of superheating temperature on net output of a 30 MW Segs plant is presented by Lippke [120T]. Damage to the sodium heat pipe receiver for a 9 kW dish-Stirling system in Spain is reported in Ref. [119T]. An overview of the 10 MW Solar Two power tower plant that uses molten nitrate salt as the storage and heat transfer medium is given in Ref. [123T]

A conceptual design for a 50 kW solar-pumped iodine laser is developed for a space-based power station. Other papers addresses evaluate a solar-driven Carnot heat engine [118T] and a boiling water solar receiver that operates a steam pump [122T].

21. Plasma heat transfer and magnetohydrodynamics

21.1. Plasma modeling and diagnostics

Two papers dealt with modeling radiation transfer. Aubrecht and Bartlova [1U] calculated the radiative transport in SF6 arc plasmas for pressures from 1 to 10 atm and temperatures from 0.3 to 35 kK using the method of partial characteristics. The errors for using this method were established to be less than 10% by comparison with exact radiation transport calculations while significant computation time savings were realized. Liani et al. [10U] determined net emission coefficients for a CH_4–H_2 plasma at temperatures between 5 and 30 kK, based on radiation transfer calculations for an isothermal cylindrical plasma. Acoustic emission from a negative point to plane discharge has been used to determine the relative contributions of heat and momentum transfer between ions and neutral species, with the former contributing dipolar emission predominantly in the high frequency range, and the latter being the source of monopolar radiation at lower frequencies. Chen and Eddy [2U] continued their investigations on generalized thermodynamic relations for non-equilibrium plasma flows, concentrating in this paper on viscous flow effects in the transition from equilibrium to frozen flow conditions for a singly ionized argon plasma. Heat transfer to a metallic wire under rarified flow conditions was discussed by Chen [3U], and it was found that secondary electron emission has to be considered at low temperatures, while radiation and electron emission are important at higher temperatures. The changes of heat and mass transfer in a turbulent plasma jet were described by Krejci et al. [8U], and the transition to turbulence due to shear layer instability and the influence of jet resonance in the arc chamber were discussed. The influences of electromagnetic forces on turbulent heat transfer from a plasma flow in a tube were discussed by Levitan [9U]. The attenuation of electromagnetic radiation in the plasma boundary layer in atmospheric flight were determined by Nusca [13U] based on CFD calculations for chemically reacting flow.

Several modeling efforts concentrated on arc–electrode interaction. Lowke [11U] presented a model for a free burning arc including the electrodes, and comparison of his predictions with observations on welding arcs validated his approach. The interaction of an arc with a cold cathode was described by Coulombe and Meunier [4U,5U], and a high pressure region in the plasma vapor region in front of the cathode spot and a strong thermo-field emission of electrons was found. In another cold cathode model, presented by Marotta and Sharakhovsky [12U], the erosion of arc heater cathodes is modeled as material evaporation due to a moving heat source representing the cathode spot.

Diagnostics of a microwave generated plasma jet [7U] using Thomson scattering showed that the plasma had a hollow structure and that electron production appeared to be larger than the losses through recombination and diffusion. The radiation transfer between a plasma produced by a laser pulse on the surface of a substrate was measured using novel transient scattering diagnostics techniques [15U]. Plasma spectroscopic measurements on an arcjet wind tunnel [14U] showed the different temperatures associated with different species. An enthalpy probe and an attached mass spectrometer was used to study the decomposition of ammonia in a high frequency generated plasma [6U].

21.2. Applications of plasma heat transfer

Modeling and diagnostics of plasmas in specific applications continued to expand. Seven papers dealt with the characterization of welding arcs, although five of them from the same group. Pulsed gas tungsten arc welding (GTAW) was modeled by Fan et al. [19U,21U] who used a two-dimensional time dependent model to predict temperature and current density contours, and the same authors investigated the influence of cathode tip geometry [20U]. Another paper from the same group of authors described the forces influencing the mass motion in the weld pool [25U,26U]. A similar situation was described with an emphasis on the interfacial region between the arc and the weld pool [28U]. For a gas metal welding arc (GMAW) the effect of use of a CO_2 shield gas was modeled, and an increase in the current value for which the transition from the globular mode to the spray mode occurs was found [23U].

The interaction between plasma spray particles and the jet of the plasma spray torch was modeled by Choi and Hong [17U], with inclusion of the phase change in the particles. Fulcheri et al. [22U] looked at the structures of carbon black powders obtained with several methods and found a correlation with process temperatures. They describe a new plasma synthesis process for controlled generation of carbon black nanostructures. A model for high temperature evaporation of a complex chemical system in the presence of oxygen and chlorine vapor was developed by Chen et al. [16U], who then applied this model to the plasma vitrification of fly ash.

A mathematical model for an electromagnetic launcher was presented by Kastnel'son et al. [24U], and the importance of magnetic field inhomogeneities on plasma stability was emphasized. Results of another model of a railgun armature and comparison with experimental data lead to the conclusion that ablation was not only caused by the arc radiation but also by other modes of heat transfer [18U]. Experimental results with an electromagnetic launcher showed temperature values between 23 kK (derived from hydrogen vapor studies) to 35 kK (for copper vapor studies) at pressures of 200 MPa [29U].

In measurements related to electronic applications, measurements and modeling of substrate heat transfer in a CVD reactor lead to the determination of thermal accommodation coefficients for five different gas–surface combinations [27U].

21.3. Magnetohydrodynamics

In an experimental investigation on a coal-fired potassium seeded MHD channel, a unique relation was found between the center dip of the potassium emission line and the cold boundary layer in the flow, allowing the establishment of real-time monitoring of the flow [30U]. A model of an inclined MHD channel considered a two-phase flow with one of the phases being electrically conducting, and heat transfer rates were obtained for a range of operating conditions [34U]. A unified theory for magnetohydrodynamic and electrohydrodynamic flows was compared to classical separate MHD and EHD model descriptions, and the relative importance of the momentum and heat transfer terms were evaluated [33U]. Analytical solutions were obtained for heat transfer from a conducting fluid to a non-isothermal stretching sheet with a constant transverse magnetic field, and comparison with numerical solutions showed good agreement [32U]. Another model included real gas effects such as friction and turbulence in a time-dependent two-dimensional formulation, and the reduction of generated power due to real gas effects were determined [31U].

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